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Modifications of Conventional Rigid and Flexible Methods for Mat Foundation Design

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A thesis Submitted in Partial Fulfillment of the Requirements for the degree of Master Program in Rehabilitation and Design of Structures

August, 2008

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

لَا يُكَلِّفُ ٱللَّهُ نَفْسًا إِلَّا وُسْعَهَا ۚ لَهَا مَا
كَسَبَتْ وَعَلَيْهَا مَا ٱكْتَسَبَتْ ۗ رَبَّنَا لَا
تُؤَاخِذْنَآ إِن نَّسِينَآ أَوْ أَخْطَأْنَا ۚ رَبَّنَا وَلَا
تَحْمِلْ عَلَيْنَآ إِصْرًا كَمَا حَمَلْتَهُۥ عَلَى
ٱلَّذِينَ مِن قَبْلِنَا ۚ رَبَّنَا وَلَا تُحَمِّلْنَا مَا لَا
طَاقَةَ لَنَا بِهِۦ ۖ وَٱعْفُ عَنَّا وَٱغْفِرْ لَنَا
وَٱرْحَمْنَآ ۚ أَنتَ مَوْلَىٰنَا فَٱنصُرْنَا عَلَى
ٱلْقَوْمِ ٱلْكَٰفِرِينَ ﴿٢٨٦﴾

صدق الله العظيم

سورة البقرة

Dedication

I would like to dedicate this work with sincere regards and gratitude to my loving parents and the rest of my family for their support and help in bringing out this study in the middle harsh political circumstances in Gaza strip and West bank, where the Palestinian bodies and brainpowers are simultaneously attacked. I furthermore dedicate this work to those who tramped on their wounds, sufferings, and agonies to build nests of hope.

ACKNOWLEDGEMENT

The research reported in this thesis has been carried out at the Civil Engineering Department, Islamic University of Gaza.

Many people have contributed to my work with this thesis and to all those I would like to express my gratitude. To some people I am specially indebted:
First of all, I would like to express my sincerest thanks and appreciation to my supervisor, Dr. Samir Shihada and Dr. Jihad Hamad, for all the encouragement, inspiring guidance they have given to me over the past three years during the course of this investigation. Furthermore I would like to thank all of my Professors in Islamic University of Gaza for support.

Thanks also extend for all my colleagues at the Islamic University of Gaza for their support. Especially, I wish to thank Mr. Adel Hamad for helping me with the laboratory tests and assisting me in carrying out the plate load test experiments at the facilities of material and soil laboratory at Islamic University of Gaza. Furthermore, and finally I would like to thank Mr. Sami Alshurafa for proof reading of the manuscript.

ABSTRACT

This study provided the findings of the theoretical and experimental investigations into the modifications of conventional rigid method for mat foundation design carried out at Islamic University of Gaza. The main objective of the investigation was to satisfy equilibrium equations to construct shear force and bending moment diagrams using the conventional rigid method by finding factors for adjusting column load and applied soil pressure under mat and producing a computer program using C#.net based on the modified proposed way of mat analysis suggested by the researcher to carefully analyze the mat by drawing the correct closed moment and shear diagrams to each strip of mat and to determine reliable coefficients of subgrade reactions for use of flexible method jointly with performing plate load test on sandy soil on site and analyzing and studying a large number of tests of plate load test on sand soil performed by material and soil laboratory of Islamic University of Gaza and to generate a simplified new relation to account for K mat as function of known settlement and compare it to the relation given by Bowels (1997). It will also discuss the differences of the obtained results from design analysis using the proposed solution of conventional rigid method and the flexible method using finite element. In addition, it will launch an interesting finding shows a significant reduction of the amount of flexural steel reinforcement associated with the conventional rigid method that will be decreased by reducing its bending moment obtained by up to 15% after applying a load factor to match the numerical obtained values of bending moment from flexible method by applying a finite element available commercials software.

Discussions emanating from the above investigation will provide interesting findings and will balance equations to construct shear force and bending moment diagrams using the new proposed solution analysis for conventional rigid method passing through factors to adjust the column load and the soil pressure together and it will also present experimental reliable coefficient of subgrade reactions taken for real soil to be employed when using flexible method analysis using available finite element computer software.

الخلاصة

تم بحمد الله ورعايته إكمال هذه الدراسة في الجامعة الاسلامية بغزة لتشمل العديد من المعلومات الجديدة والمفيدة التي تم الحصول عليها من خلال دراسة بحثية نظرية و مخبرية شاملة لتعديل الطريقة التقليدية المتبعة لتحليل و تصميم اللبشة في قطاع غزة .

من أهم ما يميز هذه الدراسة هو تحقيق معادلات الاتزان لإنشاء رسومات صحيحة معدلة لقوي القص والعزوم في الشريحة للطريقة التقليدية المتبعة في تصميم لبشة الأساسات وذلك من خلال إيجاد معاملات تصميمية تم اقتراحها من خلال الباحث لتضبط أحمال الأعمدة وضغط التربة الناشيء تحت اللبشة على الأرض الرملية لتتغلب على عدم إغلاق قيم القص والعزوم في حال اتباع الطريقة التقليدية (Conventional Rigid Method)، أيضا قام الباحث بتطوير برنامج كمبيوتر سهل الاستخدام يستطيع من خلاله المهندس المصمم إدخال الأحمال وشكل اللبشة ليحصل على رسومات قوي القص والعزوم بناء علي الطريقة المقترحة المعدلة للطريقة التقليدية المتبعة للبشة الأساسات علي التربة الرملية.

هذا البحث العلمي يضم جزء كامل يشمل العديد من التجارب (Plate Load Test) التي قام بها الباحث لإيجاد معامل رد فعل التربة الرملية K لبتم استخدامها لاحقا في تحليل اللبشة باستخدام الطريقة المرنة باستخدام العناصر الدقيقة (Finite Element) من خلال برنامجين انشائين هما برنامج Safe 8 وبرنامج Sap2000 . أيضا هذه الدراسة تضم تحليل شامل للعديد من التجارب القديمة (Plate Load Test) على التربة الرملية التي تم تجميعها من مختبر المواد والتربة بالجامعة الإسلامية حيث قام الباحث بإيجاد معادلة جديدة يمكن من خلالها الحصول علي قيم معامل رد فعل التربة الرملية K بدلالة معرفة الهبوط كما تم أيضا مقارنة العلاقة التي أوجدها الكاتب بالعلاقة المستخدمة من خلال باول (Bowel 1997).

في النهاية ناقشت هذه الدراسة الاختلافات بين الطريقة التي قام بتطويرها الكاتب للتغلب على مشكلة رسومات قوي القص والعزوم المشار إليها في كتاب (DAS 1999) مع طريقة المرونة المتبعة في تحليل اللبشات باستخدام برنامجين إنشائيين يستخدمان لتحليل اللبشة باستخدام تحليل العناصر الدقيقة جدا (Finite Element) حيث تم الحصول علي إمكانية تقليص قيم قوي القص والعزوم إلي 15 في المائة باستخدام الطريقة المقترحة من خلال الباحث، بالإضافة إلي تطوير برنامج كمبيوتر يسهل عملية تحليل اللبشة على التربة الرملية .

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Chapter 1

Introduction

1.1 Introduction

Over the past few decades, a very limited number of researches have tried to devise equilibrium equations to construct shear force and bending moment diagrams using the conventional rigid method, by finding factors for adjusting columns load and soil pressure for each strip. Mat foundation is one type of shallow foundations that is widely used in Gaza strip, Palestine. It is commonly used under structures whenever the column loads or soil conditions result in footings or piles occupying most of the founding area. For many multi-story projects, a single mat foundation is more economical than constructing a multitude of smaller number of isolated foundations. Mat foundations due to their continuous nature provide resistance to independent differential column movements, thus enhancing the structural performance. Mat can bridge across weak pockets in a nonuniform substratum, thus equalizing foundation movements. Mat foundations are predominantly used in regions where the underplaying stratum consists of clayey materials with low bearing capacity. They are also used as a load distributing element placed on piles or directly on high bearing capacity soil or rock, when considering high-rise building design option. For mat foundation which is minimal in size and complexity, long hand techniques with or without mini computer assistance may be acceptable. For large mats under major structures, more complex finite element techniques utilizing large main frame computers are normally required. For major mat foundation designs, it is to structural engineer advantages to set up a computer analysis model. There are several categories of mat foundations problems which by their nature required a sophisticated computer analysis. They are: (1) mat with a non-uniform thickness; (2) mat of complex shapes; (3) mats where it is deemed necessary that a varying subgrade modulus must be used; (4) mats where large moments or axial force transmitted to the mat. There are different approaches when an engineer considers a mat foundation design option [4], and they are: (a) conventional rigid method, in which mat is divided into a number of strips that are loaded by a line of columns and are resisted by the soil pressure. These strips are analyzed in a way similar to that analysis of the combined footing; (b) approximate flexible method as suggested by ACI Committee 336(1988) and (c) discrete element method. In this method, the mat foundation is divided to a number of elements by griding using one of the finite-difference method (FDM), finite-element method (FEM) or Finite-grid method (FGM).

This study was initiated because no literature was found in relation to balance the equilibrium equations used for constructing shear force and bending moment diagrams using the conventional rigid method, by finding factors for adjusting column load and the soil pressure individually for each strip followed by producing an optimum proposed average bending moment diagram. In addition, there is no research found applies finite element method using the latest version of available commercial new released softwares such as SAFE version 8 and Structural Analysis Program SAP 2000 version 11 to analyze and to discuss profoundly the possibility of a significant reduction in the amount of flexural steel reinforcement associated with the conventional rigid method that is expected to be decreased by reducing its bending moment obtained after applying a load modifying factors to match the numerical obtained values of bending moment from using flexible method.

1.2 Objectives:

The main objective of this work is to understand in depth the dissimilarities of mat foundations design by applying the conventional rigid method and the approximate flexible method. The research work is intended to achieve the following objectives:

1. To satisfy equilibrium equations required for constructing shear force and bending moment diagrams using the conventional rigid method.
2. To find out reliable coefficients of subgrade reactions by conducting plate load tests.
3. To find out a simplified new relation to calculate K for sandy soil based on the plate load test done by the researcher and a large number of an old available plate load test performed on sandy soil by the material and soil laboratory of Islamic University of Gaza
4. To better understand the differences between the results obtained using the conventional rigid method and the flexible method.
5. To put forward a new innovative design approach by reducing the large amounts of flexural reinforcement that are associated with the conventional rigid method.

6. To create a user friendly structural analysis computer program to analyze the mat strips based on the average optimum proposed suggested method by the researcher to construct a correct shear and bending moment.

1.3 Methodology

This thesis has been divided into four parts. The first part comprises a comprehensive literature review of the latest conducted research on conventional rigid method and the flexible method. This part was summarized based on the findings of a number of available resources related to the subject such as published research work, journal papers, conference papers, technical reports, and World Wide Web internet.

The second part of this study contains more than one solution to find balanced equations for constructing shear force and bending moment diagrams using the conventional rigid method by either finding factors for adjusting column load as an individual solution followed by adjusting the soil pressure for each strip to represent a second solution. From the first and the second solutions, the writer of this manuscript will propose an optimum solution stand for the average of the obtained numerical moment values. The above suggested solutions will be performed on a real mat foundation case study existent in Gaza city. In addition this part has a user friendly computer structural analysis program developed by the researcher to analyze mat foundation strips using the proposed optimum solution by the researcher.

The third part encloses a testing program using plate load tests conducted on selected sites to determine the coefficient of subgrade reaction to be used when constructing a finite element model using available commercial software. Moreover this part contains a comprehensive analysis for a number of reports of old plate load tests experiments done by material and soil laboratory of Islamic University of Gaza on sandy soil, the reports were divided into groups and a best fitting curve were obtained from each group followed by finding the best unified fitting curves for the best fitting curves of each group then developing a relation to calculate the coefficient of subgrade reactions K of sandy soil as a function of known settlement and compare it to the Bowels relation (1997).

The last part contains an inclusive computer analysis for a real case-study of mat foundation using flexible method by employing two available commercial finite element methods based software packages and the softwares are: 1) Structural Analysis Program SAP 2000 and 2) SAFE version 8. The results obtained from each individual software will be compared to the results obtained from the proposed optimum solution for conventional rigid method. At the end, important findings and suggested modified factors will be presented to attest that a large amount of flexural reinforcement associated with the conventional rigid method will be decreased by reducing its bending moment that obtained after applying a load modifying factor to match the results of bending moment values obtained from the flexible method by using finite element commercial softwares.

This thesis contains seven chapters. The first chapter consists of a general introduction and outlines the objectives of this study. The second chapter discusses research problem identification by introducing a complete solved case study for mat foundation design using conventional method and comprises a survey of previous work related to the subject of this thesis: conventional rigid method, and the flexible method. The third chapter sets a theoretical solution of conventional rigid method and comprises three parts, the first part applies modification factors for columns load only to construct the first suggested bending moment diagram trailed by a second solution that applies modifications only to the soil pressure to construct a second suggested bending moment diagram, and finally from the first and the second bending moment diagrams, an optimum average solution is proposed followed by writing a user friendly structural analysis computer program to analyze mat strips based on the optimum average solution suggested by the researcher. The fourth chapter outlines the experimental test set-up and presents all the experimental results of the coefficients of subgrade reaction along with analysis a number of an old plate load tests on sandy soil done by material and soil laboratory of Islamic University of Gaza followed by developing a relation to calculate coefficient of subgrade reactions of K as a function of settlement. The fifth chapter contains a comprehensive finite element study using Sap 2000 version 11 and Safe Program version 8 to analyze mat foundation. The sixth chapter includes a discussion of the obtained result. And the final chapter contains conclusions and recommendations.

Chapter 2

Literature Review

2.1 Introduction

The problem of analysis and design of mat foundation had attracted the attention of engineers and researchers for a long time. This is because mat foundations are frequently associated with major multistoried structures founded on different types of soils. The mat foundation is one type of shallow foundations and widely used in the world. The use of mat foundation as an option by an engineer dated back to late of eighteenth century. In Palestine, mainly in Gaza city, mat foundation has been a dominant option when constructing a multistory building. This study focused on optimizing conventional rigid method, this method is characterized by its simplicity and ease in execution. On the other hand, the resultant of column loads for each of the strips doesn't coincide with the resultant of soil pressure and therefore this can be attributed to the shear forces present at the interfaces of the consecutive strips. Consequently, this leads to a violation of the equilibrium equations summation of forces in the vertical direction and the summation of moments around any point are not adjacent or even close to zero, indeed a few researchers had tried in the past to find a solution for this fictitious problem. for instance [8] had proposed two sets of modification factors, one for column loads and the other for soil pressures at both ends of each of the individual strips. These modifications factors result in satisfying equilibrium equation of vertical forces, summation of forces in the vertical direction is close to zero, therefore the construction of shear force diagrams can be worked out but this is not the case when engineer try to construct a moment diagram as the equilibrium equation is not satisfied as the summation of moments around any point do not go to zero. As a result, constructing a correct bending moment diagram is a challenge. This is because the factors applied are not suited to balance the total resultant force of columns from top to the resultant force of the applied pressure under mat as both forces are never pass through the same line of action, this will be given more attention and detailed discussion later in the following chapters of this study.

In a comparison to the approximate flexible method, the conventional rigid method requires larger amounts of flexural reinforcement because the distribution of soil pressure is only permitted in one direction not in both directions as of that in approximate flexible method therefore it is clear evidence that the obtained steel reinforcements employing approximate flexible method will be with no doubt less that of using the conventional method. The flexible method requires the determination of coefficients of subgrade reaction K, in order to carry out the analysis. The coefficient of subgrade reaction is a mathematical constant that denotes the foundation's stiffness. The coefficient of subgrade reaction is the unit pressure required to produce a unit settlement. The value of the coefficient of subgrade reaction varies from place to another and not constant for a given soil, it depends upon a number of factors such as length, width and shape of foundation and also the depth of embedment of the foundation, and usually determined using empirical equations in terms of the allowable bearing capacity of the soil.

The conventional rigid method is based on Winkler's concept of shear free elastic springs in conjunction with the assumption of the mat as rigid which leads to determine contact pressure distribution.

Winkler model:

Winkler (1867) developed a model to simulate Soil-Structure Interaction. The interaction basic assumption is based on the idea that the soil-foundation interaction force p at a point on the surface is directly proportion to the vertical displacement ΔZ of the point as shown in Figure (2.1). Thus, $P = K\Delta Z$ where K is the stiffness or modulus of sub-grade reaction.

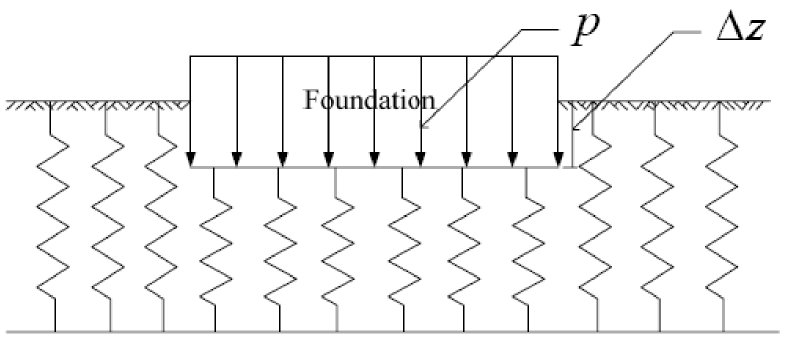

Figure (2.1) Winkler foundation layout

The interaction of the structure and its soil was treated in Winkler model by representing the soil with the linear elastic spring model with specific geometrical and elastic properties. This is a pure analytical treatment of a structural model with fictional supports without taking into account the actual behavior of soils.

The analysis and design of mat foundations is carried out using different methods techniques such as the conventional rigid method, the approximate flexible method, the finite difference method and the finite element method as can be seen in Figure (2.2). This literature review chapter encloses the American concrete institute ACI code requirements for use of conventional method, conventional rigid method assumptions and procedures, detailed worked-out example, an approximate flexible method assumptions and procedures to better understand the subject of the thesis and finally will contain a general survey of previous work in the field of mat foundation analysis and related topic, namely; conventional rigid method and approximate flexible method was carried out. The review is not intended to be complete but gives a summary of some of the previous work conducted in relation to conventional rigid method and approximate flexible method and their applications.

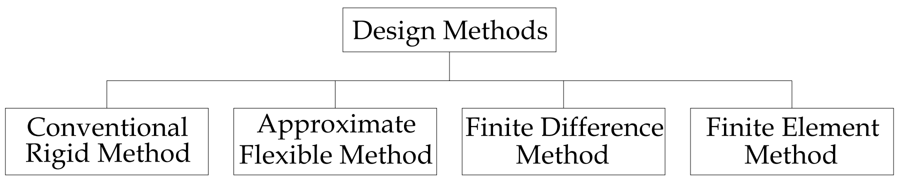

Figure (2.2) Flowchart of different design methods of mat foundation

2.2 ACI Code Requirements

According to the ACI committee 336 (1988) the design of mats could be done using the conventional rigid method if the following conditions have been satisfied:

1. The spacing of columns in a strip of the mat is less than 1.75/λ where λ the characteristic coefficient is defined by Hetenyi M. (1946) as follow, $\lambda = \sqrt[4]{\frac{B\,k_s}{4\,EI}}$ or the mat is very thick.

   Where k_s: Coefficient of subgrade reaction

   B: width of strip

   E: Modulus of elasticity of raft material

   I: Moment of inertia of a strip of width B
2. Variation in column loads and spacing is not over 20%.

If the mat does not meet the rigidity requirements of conventional rigid method it should be designed as a flexible plate using the approximate flexible method, the finite differences or the finite element methods.

2.3 Conventional Rigid Method Assumptions

The conventional rigid method assumes the following two conditions

1. The mat is infinitely rigid, and therefore, the flexural deflection of the mat does not influence the pressure distribution.
2. The soil pressure is distributed in a straight line or a plane surface such that the centroid of the soil pressure coincides with the line of action of the resultant force of all the loads acting on the foundation as shown in Figure (2.3).

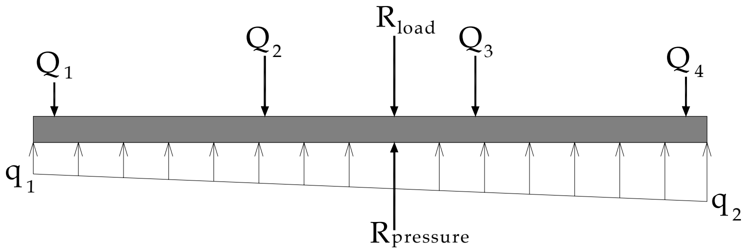

Figure (2.3): Soil pressure coincides with the resultant force of all the loads

2.4 Conventional Rigid Method Design Procedure

The procedure for the conventional rigid method consists of a number of steps with reference to Figure (2.4) as follows:

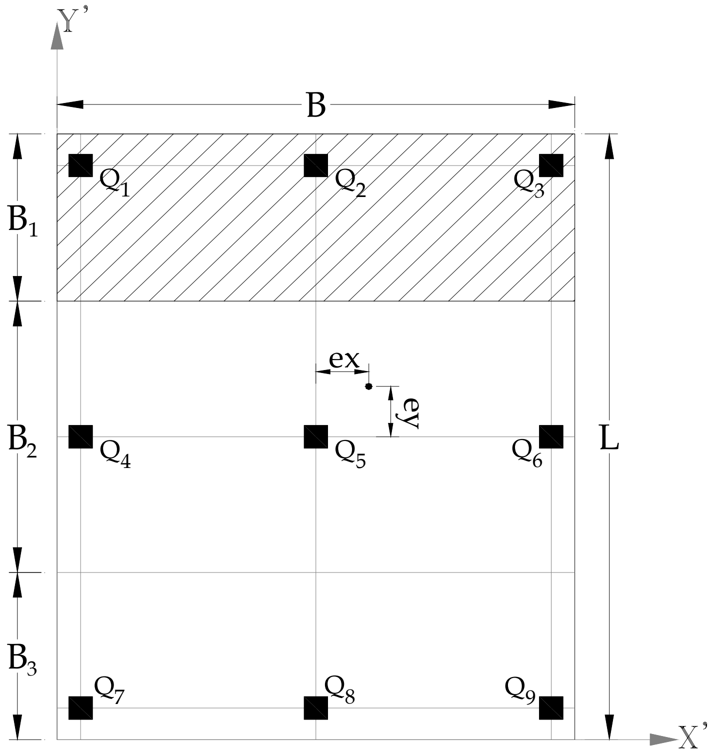

Figure (2.4): A layout of mat foundation

1. Determine the line of action of all the loads acting on the mat

$$Q = Q_1 + Q_2 + Q_3 + \ldots\ldots = \sum Q_i \quad (2.1)$$

The eccentricities e_x and e_y are found by summing moment about any convenient location (usually a line of column).

About X' and Y' coordinates

$$x = \frac{(Q_1 x_1 + Q_2 x_2 + Q_3 x_3 + \ldots\ldots)}{\sum Q} \Rightarrow e_x = x - \frac{B}{2}$$

$$y = \frac{(Q_1 y_1 + Q_2 y_2 + Q_3 y_3 + \ldots\ldots)}{\sum Q} \Rightarrow e_y = y - \frac{L}{2}$$

2. Determine the allowable pressure q on the soil below the mat at its corner points and check whether the pressure values are less than the allowable bearing pressure.

$$q = \frac{Q}{A} \pm \frac{M_x Y}{I_x} \pm \frac{M_y X}{I_y} \quad (2.2)$$

Where, A = B L =Base area of the mat foundation

I_x moment of inertia about x - axis $= BL^3/12$

I_y moment of inertia about x - axis $= LB^3/12$

M_x moment of the column loads about the x - axis $= \sum Q.e_y$

M_y moment of the column loads about the y - axis $= \sum Q.e_x$

3. Determine the mat thickness based on punching shear at critical column based on column load and shear perimeter.
4. Divide the mat into strips in x and y direction. Each strip is assumed to act as independent beam subjected to the contact pressure and the columns loads.
5. Determine the modified column load as explained below, it is generally found that the strip does not satisfy static equilibrium, i.e. the resultant of column loads and the resultant of contact pressure are not equal and they do not coincide. The reason is that the strips do not act independently as assumed and there is some shear transfer between adjoining strips.

   Considering the strip carrying column loads Q_1, Q_2 and Q_3 as seen in Figure (2.5), let B_1 be the width of the strip and let the average soil pressure on the strip q_{avg} and let B the length of the strip.

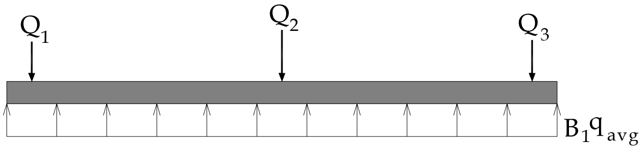

Figure (2.5): A layout of strip

Average load on the strip is:

$$Q_{avg} = \left(\frac{Q_1 + Q_2 + Q_3 + q_{avg} \, B_1 \, B}{2} \right) \qquad (2.3)$$

The modified average soil pressure ($q_{avg,\mathrm{mod}}$) is given by

$$q_{avg\,\mathrm{mod}} = q_{avg} \left(\frac{Q_{avg}}{q_{avg} \, B_1 \, B} \right) \qquad (2.4)$$

The column load modification factor F is given by

$$F = \left(\frac{Q_{avg}}{Q_1 + Q_2 + Q_3} \right) \qquad (2.5)$$

All the column loads are multiplied by F for that strip. For this strip, the column loads are FQ_1, FQ_2 and FQ_3, the modified strip is shown in Figure (2.6).

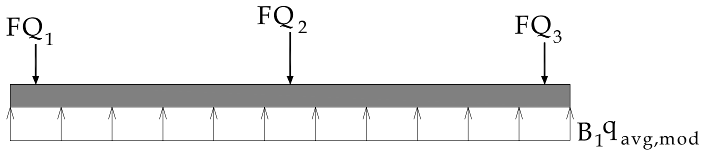

Figure (2.6): A modified strips layout

6. The bending moment and shear force diagrams are drawn for the modified column loads and the modified average soil pressure $q_{avg,\mathrm{mod}}$.
7. Design the individual strips for the bending moment and shear force.

2.5 Conventional Rigid Method of Mat foundation Worked-out example

A real case study of mat foundation design in Gaza city has been worked out in details using the conventional rigid method technique to familiarize the reader of this manuscript with the research problem. See Figure (2.7) for dimensions and geometry.

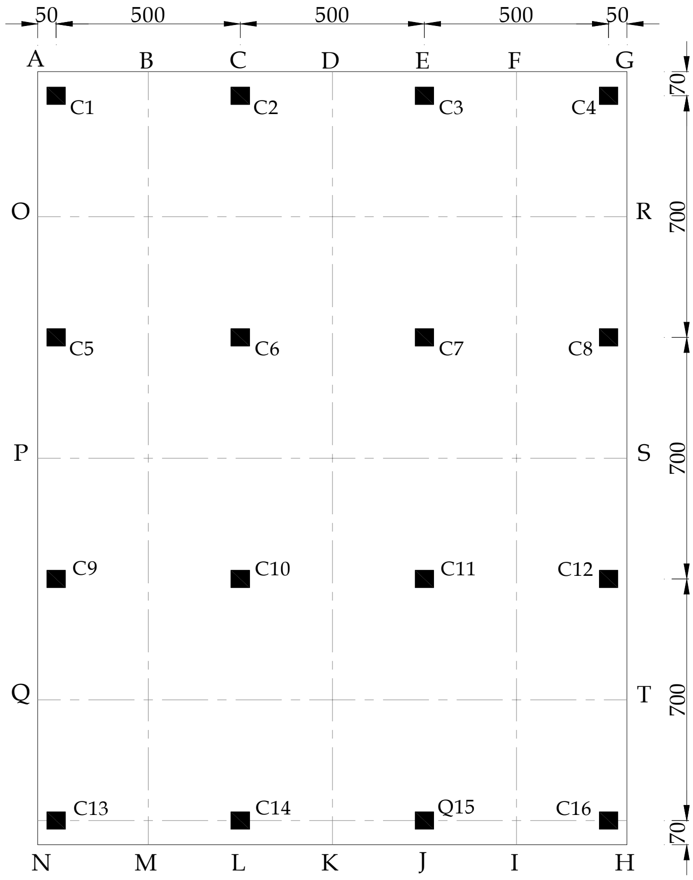

Figure (2.7): Layout of mat foundation

Columns loads are shown in Table (2.1)

Table (2.1): Column loads

Column No.	D.L (Ton)	L.L (Ton)	Column No.	D.L (Ton)	L.L (Ton)
C1	78.0	39.0	C9	133.8	66.9
C2	160.1	80.1	C10	280.4	140.2
C3	144.6	72.3	C11	286.8	143.4
C4	67.1	33.6	C12	136.0	68.0
C5	157.2	78.6	C13	60.3	30.2
C6	323.1	161.6	C14	127.5	63.8
C7	295.3	147.7	C15	131.6	65.8
C8	138.3	69.2	C16	62.6	31.3

Step 1: check soil pressure for selected dimensions

Column service loads = Σ Qi (where i = 1 to n)

According to ACI 318-05 (Section 9.2),

Factored load, U = 1.2 (Dead load) + 1.6 (Live load)

So, Ultimate load $Q_u = \Sigma [1.2\ DL_i + 1.6 LL_i]$

Ultimate to service load ratio $r_u = Q_u/Q$

The Table (2.2) shows the calculation for the loads:

Table (2.2): Load calculations

Column No.	DL (ton)	LL (ton)	Q (ton)	Q_u (ton)
1	78.0	39.0	117.00	156.00
2	160.1	80.1	240.15	320.20
3	144.6	72.3	216.90	289.20
4	67.1	33.6	100.65	134.20
5	157.2	78.6	235.80	314.40
6	323.1	161.6	484.65	646.20
7	295.3	147.7	442.95	590.60
8	138.3	69.2	207.45	276.60
9	133.8	66.9	200.70	267.60
10	280.4	140.2	420.60	560.80
11	286.8	143.4	430.20	573.60
12	136.0	68.0	204.00	272.00
13	60.3	30.2	90.45	120.60
14	127.5	63.8	191.25	255.00
15	131.6	65.8	197.40	263.20
16	62.6	31.3	93.90	125.20
		Total Loads =	3874.05	5165.40
		r_u =	1.333	

Ultimate pressure $q_u = q_a \times r_u$ =14.9 x 1.333 = 19.86 t/m^2

Location of the resultant load Q,

In x- direction

Moment summation is $\Sigma M_{y\text{-axis}}$ = 0.0 (see Table (2.3))

Table (2.3): Moment calculations in x- direction

Q (ton)	Q_u (ton)	X_i (m)	M (t.m)	M_u (t.m)
117.00	156.00	0	0.00	0.00
240.15	320.20	5	1200.75	1601.00
216.90	289.20	10	2169.00	2892.00
100.65	134.20	15	1509.75	2013.00
235.80	314.40	0	0.00	0.00
484.65	646.20	5	2423.25	3231.00
442.95	590.60	10	4429.50	5906.00
207.45	276.60	15	3111.75	4149.00
200.70	267.60	0	0.00	0.00
420.60	560.80	5	2103.00	2804.00
430.20	573.60	10	4302.00	5736.00
204.00	272.00	15	3060.00	4080.00
90.45	120.60	0	0.00	0.00
191.25	255.00	5	956.25	1275.00
197.40	263.20	10	1974.00	2632.00
93.90	125.20	15	1408.50	1878.00
		$\Sigma Q_i . X_i =$	28647.75	38197.00

$X_{bar} = [\Sigma Q_i \; X_i] / \Sigma Q_i = 28,647.75/3,874.05 = 7.395$ m

$e_x = X_{bar} - B/2 = 7.395 - 7.5 = -0.105$ m

In y- direction

Moment summation is $\Sigma M_{x\text{-axis}} = 0.0$ (see Table (2.4))

Table (2.4): Moment calculations in Y direction

Q (ton)	Q_u (ton)	Y_i (m)	M (t.m)	M_u (t.m)
117.00	156.00	21	2457.00	3276.00
240.15	320.20	21	5043.15	6724.20
216.90	289.20	21	4554.90	6073.20
100.65	134.20	21	2113.65	2818.20
235.80	314.40	14	3301.20	4401.60
484.65	646.20	14	6785.10	9046.80
442.95	590.60	14	6201.30	8268.40
207.45	276.60	14	2904.30	3872.40
200.70	267.60	7	1404.90	1873.20
420.60	560.80	7	2944.20	3925.60
430.20	573.60	7	3011.40	4015.20
204.00	272.00	7	1428.00	1904.00
90.45	120.60	0	0.00	0.00
191.25	255.00	0	0.00	0.00
197.40	263.20	0	0.00	0.00
93.90	125.20	0	0.00	0.00
		$\Sigma Q_i . Y_i =$	42149.10	56198.80

Y_{bar} = [ΣQ $_i$ y $_i$]/ ΣQ $_i$ = 42,149.1/3,874.05 = 10.88 m

$e_y = Y_{bar} - L/2$ = 10.88 – 10.5 = 0.38 m

Applied ultimate pressure, $q = \left[\frac{Q}{A} \pm \frac{M_y \, x}{I_y} \pm \frac{M_x \, y}{I_x} \right]$

Where: A = Base area = B x L=16 x 22.4 = 358.4 m^2

$M_{u,x} = Q_u \, e_y$ = 5,165.4*0.38 = 1,962.10 t. m

$M_{u,y} = Q_u \, e_x$ = 5,165.4*-0.105 = -543.5 t. m

$$I_x = \frac{1}{12} B \, L^3 = \frac{1}{12}(16)(22.4)^3 = 14{,}985.9 \, m^4$$

$$I_y = \frac{1}{12} L \, B^3 = \frac{1}{12}(22.4)(16)^3 = 7{,}645.9 \, m^4$$

Therefore, $q_{u,applied} = \left[\frac{5{,}165.4}{358.4} \pm \frac{(-543.5)\, x}{7{,}645.9} \pm \frac{1{,}962.10\, y}{14{,}985.9} \right]$

$$= 14.41 \ \pm \ (-0.071)\, x \ \pm \ 0.131\, y \qquad (t/m^2)$$

Now stresses can be summarized (see Table (2.5))

Table (2.5): Allowable soil pressure calculations

Point	Q/A (t/m²)	x (m)	- 0.071 x (t/m²)	y (m)	+ 0.131 y (t/m²)	q (t/m²)
A	14.41	-8	0.5687	11.2	1.4664	16.447
B	14.41	-5	0.3554	11.2	1.4664	16.234
C	14.41	-2.5	0.1777	11.2	1.4664	16.057
D	14.41	0	0.0000	11.2	1.4664	15.879
E	14.41	2.5	-0.1777	11.2	1.4664	15.701
F	14.41	5	-0.3554	11.2	1.4664	15.523
G	14.41	8	-0.5687	11.2	1.4664	15.310
H	14.41	8	-0.5687	-11.2	-1.4664	12.377
I	14.41	5	-0.3554	-11.2	-1.4664	12.591
J	14.41	2.5	-0.1777	-11.2	-1.4664	12.768
K	14.41	0	0.0000	-11.2	-1.4664	12.946
L	14.41	-2.5	0.1777	-11.2	-1.4664	13.124
M	14.41	-5	0.3554	-11.2	-1.4664	13.301
N	14.41	-8	0.5687	-11.2	-1.4664	13.515
O	14.41	-8	0.5687	7	0.9165	15.898
P	14.41	-8	0.5687	0	0.0000	14.981
Q	14.41	-8	0.5687	-7	-0.9165	14.065
R	14.41	8	-0.5687	7	0.9165	14.760
S	14.41	8	-0.5687	0	0.0000	13.844
T	14.41	8	-0.5687	-7	-0.9165	12.927

The soil pressures at all points are less than the ultimate pressure = 19.86 t/m^2

Step 2- Draw shear and moment diagrams

The mat is divided into several strips in the long direction and the following strips are considered: ABMN, BDKM, DFIK and FGHI in the analysis. The following calculations are performed for every strip:

A) The average uniform soil reaction,

$$q_u = \frac{q_{u,Edge1} + q_{u,Edge2}}{2}$$

refer to the previous table for pressure values

for Strip ABMN (width = 3m)

$$q_{u,Edge1} = \frac{q_{(at\,A)} + q_{(at\,B)}}{2} = \frac{16.447 + 16.234}{2} = 16.35\,t/m^2$$

$$q_{u,Edge2} = \frac{q_{(at\,M)} + q_{(at\,N)}}{2} = \frac{13.301 + 13.515}{2} = 13.41 \quad t/m^2$$

$$q_u = \frac{16.35 + 13.41}{2} = 14.87 \ t/m^2$$

for Strip BDKM (width = 5 m)

$$q_{u,Edge1} = q_{(at\,C)} = 16.057 \ t/m^2$$

$$q_{u,Edge2} = q_{(at\,L)} = 13.124 \ t/m^2$$

$$q_u = \frac{16.057 + 13.124}{2} = 14.59 \ t/m^2$$

for Strip DFIK (width = 5 m)

$$q_{u,Edge1} = q_{(at\,E)} = 15.701 \ t/m^2$$

$$q_{u,Edge2} = q_{(at\,J)} = 12.768 \ t/m^2$$

$$q_u = \frac{15.701 + 12.768}{2} = 14.23 \quad t/m^2$$

for Strip FGHI (width = 3 m)

$$q_{u,Edge1} = \frac{q_{(at\,F)} + q_{(at\,G)}}{2} = \frac{15.523 + 15.310}{2} = 15.42 \quad t/m^2$$

$$q_{u,Edge2} = \frac{q_{(at\,I)} + q_{(at\,H)}}{2} = \frac{12.591 + 12.377}{2} = 12.48 \ t/m^2$$

$$q_u = \frac{15.42 + 12.48}{2} = 13.95 \quad t/m^2$$

B) Total soil reaction is equal to $q_{u,avg}$ (B_i B)

Strip ABMN: B_1= 3 m

Strip BDKM: B_2= 5 m

Strip DFIK: B_3= 5 m

Strip FGHI: B_4= 3m

For all strips B = 22.4 m

C) Total column loads $Q_{u,total} = \Sigma Q_{ui}$

D) $Average\ load = \dfrac{q_{u,avg}\,(B_i\ B) + Q_{u,total}}{2}$

E) Load multiplying factor $F = \dfrac{Average\ load}{Q_{u,total}}$

F) The modified loads on this strip $Q'_{ui} = F \times Q_{ui}$

G) Modified Average soil pressure $q_{uavg,\text{mod}} = \left[\dfrac{Average\ load}{q_{avg}\ B_i\ B}\right]$

The calculations for the selected strips are summarized in Table (2.6).

Table (2.6): Summarized calculations of the selected strips

Strip	B_i (m)	Point	q_{Edge} (t/m^2)	q_{avg} (t/m^2)	$q_{avg}\ B_i\ B$ (tons)	$Q_{u,total}$ (ton)	Average Load (ton)	$q_{avg,mod}$ (t/m^2)	F
ABMN	3	A,B	16.34	14.87	999.56	858.6	929.08	15.19	1.082
		M,N	13.41					12.46	
BDKM	5	C	16.06	14.59	1634.09	1782.2	1708.15	16.78	0.958
		L	13.12					13.72	
DFIK	5	E	15.70	14.23	1594.28	1716.6	1655.44	16.30	0.964
		J	12.77					13.26	
FGHI	3	F,G	15.42	13.95	937.46	808	872.73	14.35	1.080
		I,H	12.48					11.62	

Based on Table (2.6), the adjusted column loads and pressure under each strip are represented in Table (2.7) through Table (2.10):

Table (2.7): Strip ABMN allowable stress calculations

Strip	Column No.	DL (ton)	LL (ton)	Q (ton)	Q_u (ton)	Q'_u (ton)	Soil reaction (tons)
ABMN	1	78	39	117	156	168.81	929.08
	5	157.2	78.6	235.8	314.4	340.21	
F =1.082	9	133.8	66.9	200.7	267.6	289.57	
	13	60.3	30.15	90.45	120.6	130.50	
	Total =	429.3	214.65	643.95	858.6	929.08	

Table (2.8): Strip BDKM allowable stress calculations

Strip	Column No.	DL (ton)	LL (ton)	Q (ton)	Q_u (ton)	Q'_u (ton)	Soil reaction (tons)
BDKM	2	160.1	80.05	240.15	320.2	306.89	1708.15
	6	323.1	161.55	484.65	646.2	619.35	
	10	280.4	140.2	420.6	560.8	537.50	
F =0.958	14	127.5	63.75	191.25	255	244.40	
	Total =	891.1	445.55	1336.65	1782.20	1708.15	

Table (2.9): Strip DFIK allowable stress calculations

Strip	Column No.	DL (ton)	LL (ton)	Q (ton)	Q_u (ton)	Q'_u (ton)	Soil reaction (tons)
DFIK	3	144.6	72.3	216.9	289.2	278.90	1655.44
	7	295.3	147.65	442.95	590.6	569.56	
	11	286.8	143.4	430.2	573.6	553.16	
F =0.964	15	131.6	65.8	197.4	263.2	253.82	
	Total =	858.3	429.15	1287.45	1716.60	1655.44	

Table (2.10): Strip FGHI allowable stress calculations

Strip	Column No.	DL (ton)	LL (ton)	Q (ton)	Q_u (ton)	Q'_u (ton)	Soil reaction (tons)
FGHI	4	67.1	33.55	100.65	134.2	144.95	872.73
	8	138.3	69.15	207.45	276.6	298.76	
	12	136	68	204	272	293.79	
F =1.080	16	62.6	31.3	93.9	125.2	135.23	
	Total =	404	202	606	808.00	872.73	

Tables (2.11) through (2.14) and the Figures (2.8) to (2.15) represents the shear and moment numerical values and the construction of shear force diagram and the bending moment diagrams for the four different strips.

Table (2.11): Shear and Moment numerical values for Strip ABMN

Strip ABMN

$B_1 =$ 3.0 m   B = 22.4 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m²)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	15.19	0.000			0.00
1	168.81			15.10	31.807	-136.999		11.14
		7	7.7				3.76	-197.68
5	340.21			14.25	171.228	-168.980		141.38
		7	14.7				11.72	-196.41
9	289.57			13.40	121.358	-168.209		-14.86
		7	21.7				18.97	-371.38
13	130.50			12.55	104.239	-26.261		-228.32
		0.7	22.4	12.46	0.000			-237.51

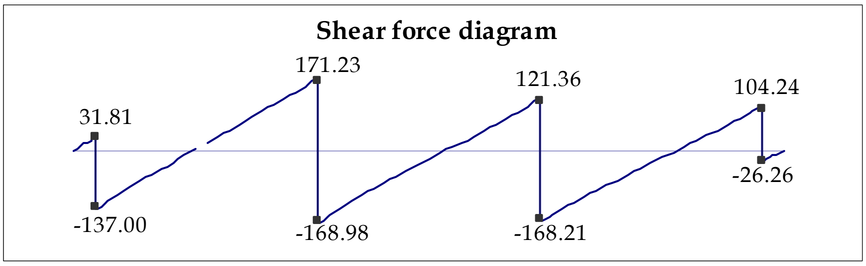

Figure (2.8): Shear force diagram for strip ABMN

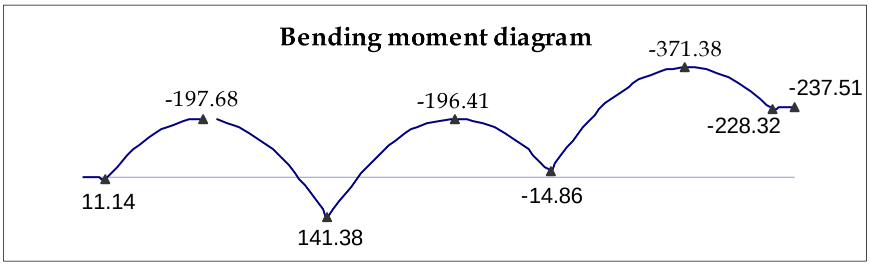

Figure (2.9): Moment diagram for strip ABMN

Table (2.12): Shear and Moment numerical values for Strip BDKM

Strip BDKM

$B_2 =$ 5.00 m

B = 22.40 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	16.78	0.000			
2	306.89			16.69	58.577	-248.318		20.52
		7	7.7				3.71	-352.03
6	619.35			15.73	319.009	-300.340		287.50
		7	14.7				11.58	-292.46
10	537.50			14.77	233.456	-304.042		72.96
		7	21.7				18.90	-561.00
14	244.40			13.81	196.222	-48.182		-284.85
		0.7	22.4	13.72	0.000			-301.69

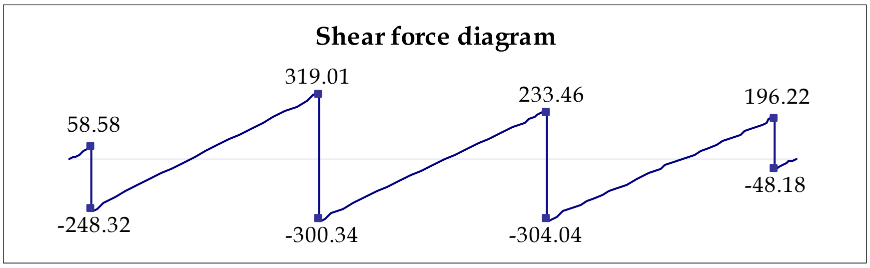

Figure (2.10): Shear force diagram for strip BDKM

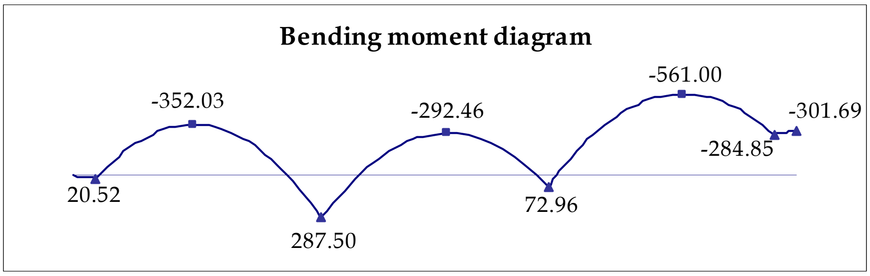

Figure (2.11): Moment diagram for strip BDKM

Table (2.13): Shear and Moment numerical values for Strip DFIK

Strip DFIK

$B_3 =$ 5.00 m   B = 22.40 m

Column No.	Q'$_u$ (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	16.30	0.000			
3	278.90			16.21	56.895	-222.001		19.93
		7	7.7				3.47	-286.51
7	569.56			15.26	328.633	-240.926		412.57
		7	14.7				10.90	28.47
11	553.16			14.30	276.400	-276.764		556.16
		7	21.7				18.64	13.94
15	253.82			13.35	207.253	-46.570		332.30
		0.7	22.4	13.26	0.000			316.02

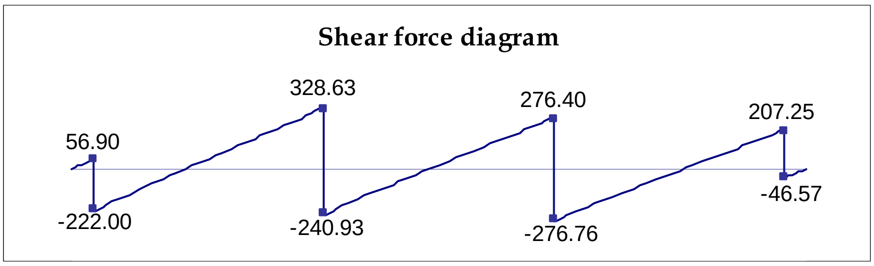

Figure (2.12): Shear force diagram for strip DFIK

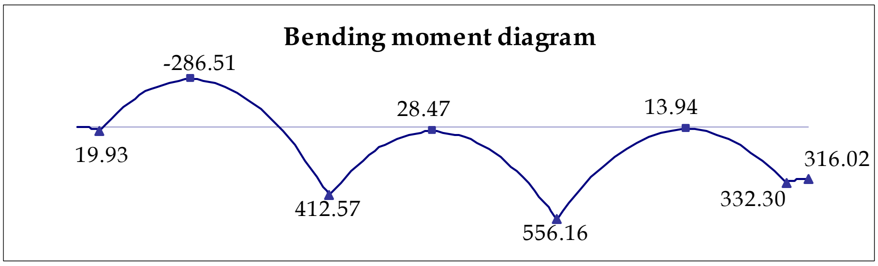

Figure (2.13): Moment diagram for strip DFIK

Table (2.14): Shear and Moment numerical values for Strip FGHI

Strip FGHI

$B_4 =$ 3.00 m | B = 22.40 m

Column No.	Q'$_u$ (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	14.35	0.000			
4	144.95			14.27	30.050	-114.901		10.53
		7	7.7				3.42	-144.90
8	298.76			13.41	175.745	-123.014		233.93
		7	14.7				10.80	44.13
12	293.79			12.56	149.714	-144.076		337.84
		7	21.7				18.60	58.89
16	135.23			11.71	110.735	-24.496		231.59
		0.7	22.4	11.62	0.000			223.03

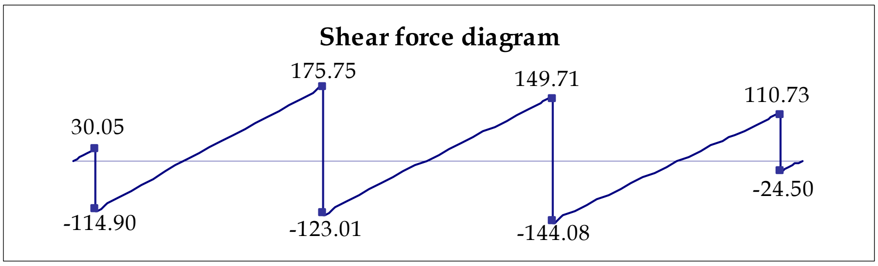

Figure (2.14): Shear force diagram for strip FGHI

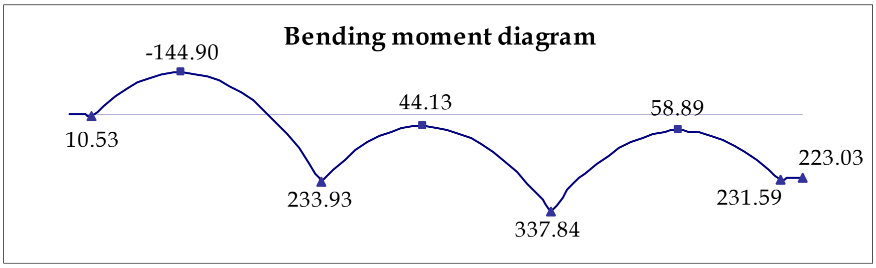

Figure (2.15): Moment diagram for strip FGHI

By looking at the calculations above it is a clear evidence that the construction of the bending moment diagrams has failed to be closed and as a result the researcher of this written manuscript is trying to study this point and will supply a modifications factors to the bending moments diagram as will be shown later in the following chapter of this thesis. The following section of this chapter is a general discussion of the approximate flexible method assumptions.

2.6 Approximate Flexible Method Assumptions and Procedures:

This method assumes that the soil behaves like an infinite number of individual springs each of which is not affected by the other as shown in Figure (2.16), the elastic constant of the spring is equal to the coefficient of subgrade reaction of the soil. Further, the springs are assumed to be able to resist tension or compression.

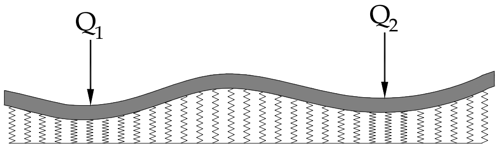

Figure (2.16): An infinite number of individual springs

This method is based on the theory of plates on elastic foundations. The step by step procedure is given by Bowels (1997) as follows:

1. Determine the mat thickness based on punching shear at critical column based on column load and shear perimeter.
2. Determine the flexural rigidity D of the mat

$$D = \frac{E\,t^3}{12(1-\mu^2)} \quad (2.6)$$

Where E = modulus of elasticity of mat material,

μ = poison's ratio of mat material, and

t = thickness of mat.

3. Determine the radius of effective stiffness (L') from the following relation

$$L' = \sqrt[4]{\frac{D}{k_s}} \quad (2.7)$$

The zone of influence of any column load will be on the order of 3L' to 4L'.

4. Find the tangential and radial moments at any point caused by a column load using the following equations.

Tangential moment,

$$M_t = -\frac{P}{4}\left(Z_4 - \frac{(1-\mu)Z'_3}{r/L'}\right) \quad (2.8)$$

Radial moment,

$$M_r = -\frac{P}{4}\left(\mu Z_4 - \frac{(1-\mu) Z'_3}{r / L'} \right) \quad (2.9)$$

Where r = radial distance from the column load, P = column load.

The variations of Z_4 and Z_3' with r / L are shown in Figure (2.17).

In Cartesian coordinates, the above equations can be written as

$$M_x = M_t \sin 2\theta + M_r \cos 2\theta \quad (2.10)$$

$$M_y = M_t \cos 2\theta + M_r \sin 2\theta \quad (2.11)$$

Where θ is the angle which the radius r makes with x- axis.

5. Determine the shear force (V) per unit width of the mat caused by a column load as

$$V = \frac{P Z_4'}{4 L'} \quad (2.12)$$

The variations of Z_4' with r / L are shown in Figure (2.17).

6. If the edge of the mat is located in the zone of influence of a column, determine the moment and shear along the edge, assuming that the mat is continuous.
7. Moment and shear, opposite in sign to those determined, are applied at the edges to satisfy the known condition.
8. Deflection at any point is given by the following equation

$$\delta = \frac{P L'^2}{4 D} Z_3 \quad (2.13)$$

9. If the zones of influence of two or more column overlap, the method of superposition can be used to obtain the total moment and shear.

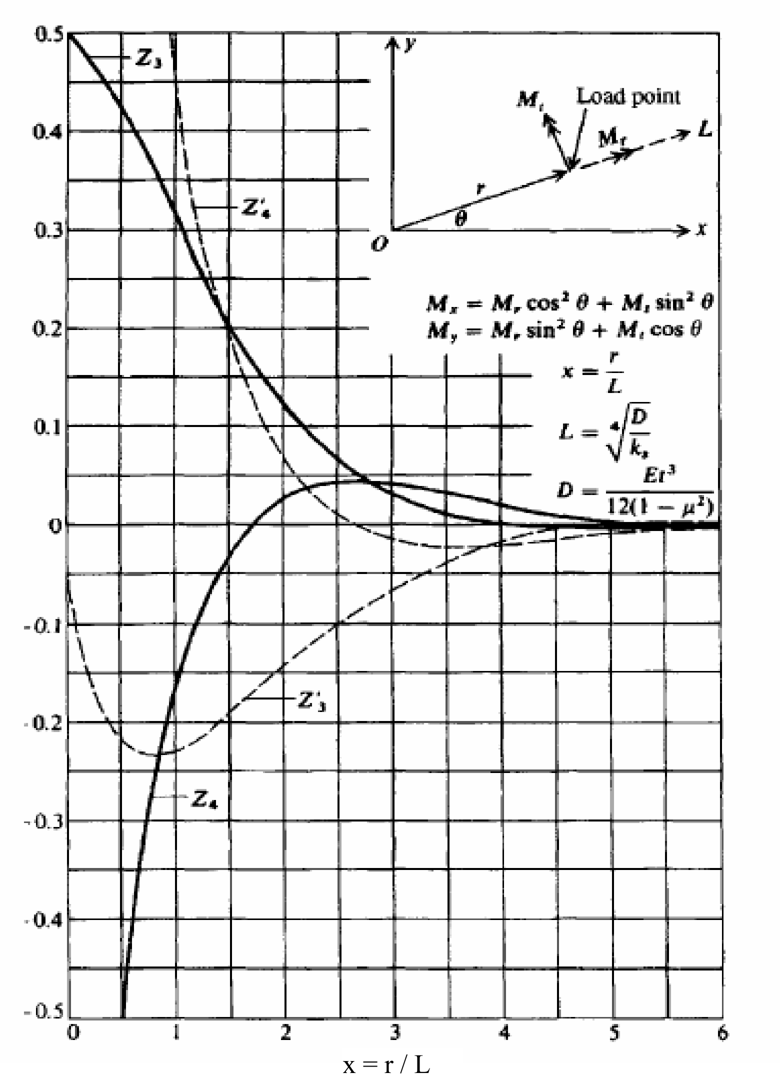

Figure (2.17): Variations of Z_4' with r / L (Ref. [4])

2.7 Coefficient of Subgrade Reaction

The coefficient of subgrade reaction known as subgrade modulus or modulus of subgrade reaction is a mathematical constant that denotes the foundation's stiffness. The common symbol for this coefficient is k; it defined as the ratio of the pressure against the mat to the settlement at a given point, $k = \frac{q}{\delta}$ the unit of k is t/m^3, where: q is the soil pressure at a given point and δ is the settlement of the mat at the same point.

The coefficient of subgrade reaction is the unit pressure required to produce a unit settlement and the value of the coefficient of subgrade reaction is not a constant for a given soil; it depends upon a number of factors such as length, width and shape of foundation in addition to the depth of embedment of the foundation. Terzaghi K. (1955) proposed the following expressions:

For cohesive soils,

$$k = \mathrm{k}_{0.3}\left(\frac{0.3}{B}\right) \qquad (2.14)$$

For sandy soils,

$$k = \mathrm{k}_{0.3}\left(\frac{B+0.3}{2B}\right)^2 \qquad (2.15)$$

Accounting for depth,

$$k = \mathrm{k}_{0.3}\left(\frac{\mathrm{B}+0.3}{2\mathrm{B}}\right)^2\left(\frac{0.3+2D}{B}\right) \le 2\,\mathrm{k}_{0.3}\left(\frac{B+0.3}{2B}\right)^2 \qquad (2.16)$$

For rectangular foundation, Lx B, on sandy soil

$$k_{\mathrm{LxB}} = \mathrm{k}\left(\frac{1+\mathrm{B}/2\mathrm{L}}{1.5}\right) \qquad (2.17)$$

Where:

L, B and D: represent footing length, width and the depth respectively and

K is the value of a full-sized footing and $k_{0.3}$ is the value obtained from 0.3mx0.3m load tests. This value can be determined by conducting a plate load test, using a square plate of size 0.30*0.30 m or circular of diameter 0.3m. After load settlement curve is constructed, the coefficient of subgrade reaction is determined using the equation $k = \frac{\mathrm{q}}{\delta}$.

Das, B.M (1999) presents rough values of the coefficient of subgrade reaction k for different soils as seen in Table (2.15).

Table (2.15): Coefficient of subgrade reaction $k_{0.3}$ for different soils (Ref. [8])

Type of soil	**Condition of soil**	**Value of k (t/m^3)**
Dry or moist sand	Loose	800 to 2500
	Medium	2500 to 12500
	Dense	12500 to 37500
Saturated Sand	Loose	1000 to 1500
	Medium	3500 to 4000
	Dense	13000 to 15000
Clay	Stiff	1200 to 2500
	Very Stiff	2500 to 5000
	Hard	> 5000

An approximate relation between the coefficient of subgrade reaction and allowable bearing capacity was suggested by Bowels (1997) as $k = 40\,(\mathrm{F.S})\,q_{all} = 120\,q_{all}$ where F.S represents the factor of safety while q_{all} stands for allowable bearing capacity of soil, this equation was developed by reasoning that q_{all} is valid for a settlement of about 25.4 mm, and safety factor equal 3. For settlement 6 mm, 12 mm and 20 mm, the factor 40 can be adjusted to 160, 83 and 50 respectively. The factor 40 is reasonably conservative but smaller assumed displacement can always be used.

The conventional rigid method usually gives higher values of bending moment and shear than the actual ones, therefore making the design uneconomical, and some times in some local locations give lower values than the real ones and as a result the design becomes unsafe. It was also evident that the conventional method is unable to take in to account the deflected shape of mat which indeed not only modifies the soil reaction but also re-distributes the load coming from the superstructure columns. In all the previous researches, the subgrade reactions had been simulated by shear-free Winkler's spring, Mehrotra B. L. (1980) had analyzed the entire system as a space frame with mat, floors and walls using stiffness and finite element analyses on a digital computer to understood the behavior of the mat. He introduced an approximation method of stiffness analysis of mat foundation for multi panel framed building. His research paper showed a reduction in the intensity of the maximum moment in mat 25 % compared with that given by conventional rigid method for the frame under the study. His stiffness analysis of a complete ten-story 12 bay framed structure along with the raft foundation was based on a digital computer and producing moment, shear and axial force distribution of the superstructure due to deformation of the raft that showed a reasonable saving in both concrete and steel in mat design.

Vesic, A. B. (1961) discussed an infinite beam resting on an isotropic elastic solid under a concentrated load and had supplied integrals solutions confirmed by numerical evaluation and approximated analytical functions. He also investigated the reliability of the conventional approach using the coefficient of subgrade reactions, K. He stated that the Winkler's hypothesis assumes that footings and mat foundation as well as grillage beams, resting on subgrades, the behavior of which is usually well simulated by that of elastic solids, and frequently analyzed by the elementary theory of beams on elastic subgrades. Based on the assumption, the contact pressure at any point of the beam is proportional to the deflection of the beam at the same point. However he argued that the theoretical investigation showed clearly that the pressure distribution at the contact between slabs and subgrades may be quite different from those assumed by the conventional analysis (Winkler's hypothesis generally not satisfied). In his paper he was able to satisfy the Winker's hypothesis for beams resting on an elastic subgrade and he found appropriate values in some cases can be assigned to the coefficient subgrade reactions K. He concluded that the beams of infinite length on an elastic isotropic semi infinite subgrade are analyzed by means of elementary theory based on Winker's hypothesis using the following equations:

$$K_{\infty} = \frac{0.9}{C}\left[\frac{E_S b^4}{E_b I}\right]^{0.083} \frac{E_S}{1-\mu_s^2} \qquad (2.18)$$

Where :

E_s : modulus of elasticity of soil

E_b : modulus of elasticity of beam

μ_s : poisson ratio

b : beam width

I : moment of inertia

C : constant

Also, he concluded that when beams of infinite length resting on an elastic isotropic half-space are analyzed by means of the elementary theory, based on coefficient of subgrade reaction K, bending moments in the beam are overestimated, while contact pressure and deflections are underestimated. The amount of error depends on the relative stiffness of the beam. Concerning beams of finite length, it is shown that the conventional analysis based on the elementary theory is justified if the beam is sufficiently long.

Yim Solomon C. (1985) developed a simplified analysis procedure to consider the beneficial effects of foundation-mat uplift in computing the earthquake response of multistory structures. This analysis procedure is presented for structures attached to a rigid foundation mat which is supported on flexible foundation soil modeled as two spring-damper elements, Winkler foundation with distributed spring-damper elements, or a viscoelastic half space. In this analysis procedure, the maximum, earthquake induced forces and deformations for an uplifting structure are computed from the earthquake response spectrum without the need for nonlinear response history analysis. It is demonstrated that the maximum response is estimated by the simplified analysis procedure to a useful degree of accuracy for practical structural design. He showed also that a reasonable approximation to the maximum response of multistory structure can be obtained by assuming that the soil structure interaction and foundation mat uplift influence only the response contribution of the fundamental mode of vibration and the contributions of the higher modes can be computed by standard procedures disregarding the effects of interaction and foundation uplift.

Mandal, J.J.(1999) proposed a numerical method of analysis for computation of the elastic settlement of raft foundations using a Finite Element Method – Boundary Element Method coupling technique. His structural model adopted for the raft was based on an isoparametric plate bending finite element and the raft-soil interface was idealized by boundary elements. Mindlin's half-space solution was used as a fundamental solution to find the soil flexibility matrix and consequently the soil stiffness matrix. The transformation of boundary element matrices were carried out to make it compatible for coupling with plate stiffness matrix obtained from the finite element method. His method was very efficient and attractive in the sense that it can be used for rafts of any geometry in terms of thickness as well as shape and loading. He also considered the depth of embedment of the raft in the analysis. In his paper, a computer program had been developed and representative examples such as raft on isotropic homogeneous half space, raft on layered media and raft on layered media underlain by a rigid base had been studied to demonstrate the range of applications of his proposed numerical method, to compute the settlement of raft foundation on a layered media the depth of the soil up to five times the width had been considered. Also he proposed a method for comparing the rigid displacement of centrally loaded square plate by introducing the numerical factor α as given below:

$$\alpha = \frac{2 E_s w_r}{(1-\mu_s^2)P} \qquad (2.19)$$

Where

α : numerical factor

P : load applied

w_r : rigid plate displacement

E_s : modulus of elasticity of soil

μ_s : poisson ratio.

Based on the literature review conducted by the researcher, it was clear evidence that there is no unambiguous literature was found to help civil engineers to understand in depth the dissimilarities of mat foundations design by applying the conventional rigid method and the approximate flexible method besides no literature was found to supply solutions to satisfy equilibrium equations when engineer construct shear force and bending moment diagrams using the conventional rigid method and to find out a precise reliable coefficients of subgrade reactions by conducting plate load tests to be used later on as an input in a computer software to analyze the mat foundation based on the approximate flexible analysis. The researcher was motivated to put forward anew innovative design approach by reducing the large amounts of flexural reinforcement that are associated with the conventional rigid method and approximate flexible method to the case studied examples solved within the research using the new modified methods suggested by the researcher as will be discussed later on in the coming chapters of this research.

Chapter 3

Proposed Solutions of Conventional Rigid Method

3.1 Introduction

The conventional rigid method is characterized by its straightforwardness and ease in implementation by civil engineering design practitioners. In contrast, the resultant of column loads for each of the strips is not equal and does not coincide with the resultant of soil pressure and this can be attributed to the shear forces present at the interfaces of the successive adjacent strips. Accordingly, this will lead to breach the equilibrium equations as it can be easily visualized when a designer summing up all the applied forces in the straight down direction, the output of the moment diagrams around end point of the strip is not approaching zero. Some researchers have tried to find out a solution for this made up problem. For instance [8] proposed two sets of modification factors, one for column loads, and the other for soil pressures at both ends of each of the individual strips. These modifications factors result in satisfying the equilibrium equation on vertical forces, summation of forces in the vertical direction is close to zero, consequently the construction of shear force diagrams can be worked out but this however is not true when a designer engineer attempts to construct a bending moment diagram as the equilibrium equation is not satisfied. Summations of moments around end point do not go to zero and as a result constructing a correct bending moment diagram is a real challenge. This is because the factors applied are not suited to balance the total resultant force of columns from top to the resultant force of the applied pressure under mat as both forces are not passing through the same line of action.

This chapter will offer a number of solutions to crack down the problem when constructing bending moment diagram for each individual strip for the mat by finding out factors that will make the resultant force of columns from top and the resultant force of the applied pressure under mat are equal and overlap. The researcher developed an optimized original excel sheet to analyze and design a real case of establishing a mat foundation for a relatively large size building. The researcher will supply two individual solutions based on the finding factors that modify column loads and soil pressure separately and to construct two individual shear and bending moments as result followed by proposing a new suggested better fit solution for the analysis of the conventional rigid method. In additions a user friendly computer structural analysis program was developed by the researcher to analyze mat foundation strips using the mentioned above proposed optimum solution by the researcher. The detailed analysis of the building can be found in appendix B. The researcher will illustrate a detail analysis for only single strip to propose the three suggested solutions as will be seen on the sequent sections within this chapter.

3.2 Strip Design Analysis (B D K M)

The strip B D K M was randomly taken from chapter 2 as shown in Figure (2.7) to illustrate the analysis and make it easy to follow up while the other strips were also studied independently and a complete analysis for the other strips can be found in appendix A . After performing a check on the bearing capacity of mat foundation, it was found that the values of bearing capacity under mat is less than the allowable bearing capacity and as a result, the mat then has been divided into strips in X and Y directions, the solutions discussed by the researcher in the above paragraph to balance the equations and construct an accurate three modified bending moment diagrams are arguing on the following subsequent paragraphs in this chapter.

3.2.1 First solution

Treating the strip shown in Figure (3.1) as a combined footing by neglecting the applied soil pressure under mat and calculate the new soil pressure under ends of the strip based on the columns loads from the following equation

$$q_{1,2(new)} = \frac{\sum Q}{A} \pm \frac{\sum Q\, e_x\, (B/2)}{I_y} \qquad (3.1)$$

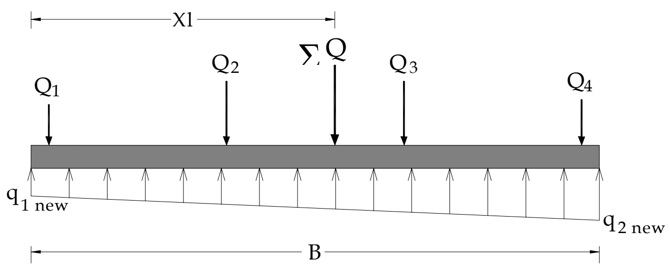

Figure (3.1): Layout of strip (Q_1 Q_2 Q_3 Q_4)- First solution

Where:

$$\sum Q = Q_1 + Q_2 + Q_3 + Q_4$$

$$A = B \times B_i$$

$$I_y = Moment\ of\ inertia\ = \frac{B_i B^3}{12}$$

$$e_x = \frac{B}{2} - X_1 \quad \Rightarrow X_1 = \frac{\sum Q_i X_i}{\sum Q_i}$$

By using the above equation, the resultants of the soil pressure under the strip and columns loads will act on the same line, and then the shear force and bending moment diagrams can be easily constructed. The strip labeled BDKM as can be seen in Figure (3.2) was taken from the complete performed analysis on mat to follow the solution for the above mentioned approach by visualizing numerical numbers. The other strips detailed analysis can be found in appendix A.

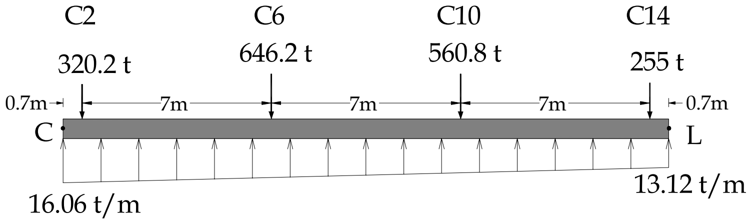

Figure (3.2): Loads on the strip BDKM before using the modification factors

$$\sum Q = 320.2 + 646.2 + 560.8 + 255 = 1{,}782.2\ ton$$

$$X_1 = \frac{320.2 * 0.7 + 646.2 * 7.7 + 560.8 * 14.7 + 255 * 21.7}{1{,}782.2} = 10.65m$$

$$e_x = \frac{22.4}{2} - 10.65 = 0.55\,m$$

$$A = 22.4 * 5 = 112\ m^2$$

$$I = \frac{5 * 22.4^3}{12} = 4{,}683.1\ m^4$$

$$q_1 = \frac{1{,}782.2}{112} + \frac{1{,}782.2 * (0.55) * (22.4 * 0.5)}{4{,}683.1} = 18.256\ t/m^2$$

$$q_2 = \frac{1{,}782.2}{112} - \frac{1{,}782.2 * (0.55) * (22.4 * 0.5)}{4{,}683.1} = 13.57\ t/m^2$$

The modified soil pressure and column loads for strip B D K M is shown in Figure (3.3).

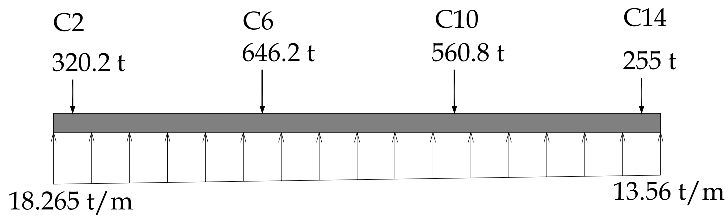

Figure (3.3): Loads on the strip B D K M after using the modification factors-First solution

The shear force and bending moment diagrams can be seen by looking at Figures (3.4) and (3.5). The intensity of new soil pressure (q_{ux})under the strip at distance x from the left of the strip is calculated as follows:

$$q_{ux} = q_1 + \left(\frac{q_1 - q_2}{B}\right)x$$

Where : q_1 is the bearing pressure at the strip first face

q_2 is the bearing pressure at the strip end face

B is the length of the strip

$$q_{ux} = 18.256 - 0.21x$$

The shear force is obtained by integrating q_{ux} as follows:

$$V_{ux} = 18.256\,x - \frac{0.21}{2}x^2 + Shear\ due\ to\ column\ loads$$

The bending moment is obtained by integrating V_{ux} as follows:

$$M_{ux} = 18.256\frac{x^2}{3} - \frac{0.21}{6}x^3 + \text{Bending due to column loads}$$

The section of maximum bending moment corresponds to the section of zero shear, $V_u = 0.0$.

Table (3.1) and Figures (3.4) and (3.5) represent the shear and bending moment numerical values and show the construction of shear force and bending moment diagrams for the strip B D K M.

Table (3.1) Shear and Moment numerical values for Strip BDKM-First solution

Strip BDKM

$B_2 =$ 5.00 m | B = 22.40 m

Column No.	Q'$_u$ (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	18.26	0.000			0.00
2	320.20			18.12	63.669	-256.531		22.31
		7	7.7				3.58	-344.99
6	646.20			16.65	351.859	-294.341		385.98
		7	14.7				11.32	-142.45
10	560.80			15.18	262.597	-298.203		304.88
		7	21.7				18.74	-292.10
14	255.00			13.71	207.281	-47.719		16.67
		0.7	22.4	13.56	0.000			0.00

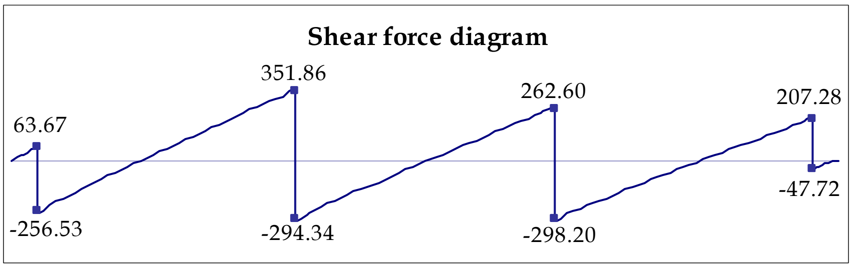

Figure (3.4): Shear force diagram for strip BDKM -First solution

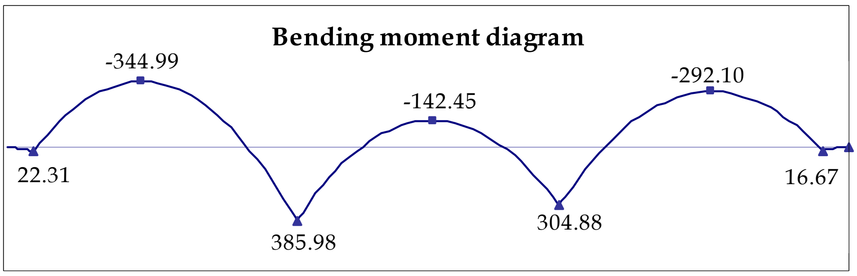

Figure (3.5): Moment diagram for strip BDKM -First solution

3.2.2 Second Solution

This solution modifies the columns loads on the strip only, by finding out factors for columns loads based on the soil pressure under the mat. Two factors make the resultant of the modified column load equal and coincide to resultant of the soil pressure under the strip. The first factor will be multiplied by the columns loads on the left of the resultant of the modified column loads and second will be multiplied by the columns loads on the right of the resultant of the modified column loads, then constructing shear force and bending moment diagrams as follows:

Treating the chosen strip BDKM shown in Figure (3.6) by mathematical equations as:

$$\sum F_y = 0.0$$

$$F_1 \sum Q_{Left} + F_2 \sum Q_{Right} = \left(\frac{q_1 + q_2}{2}\right) B_i \; B \tag{3.2}$$

$$\sum M_{at\ left\ point} = 0.0$$

$$F_1 \sum \left(Q_{i\,Left} \,.\, x_i\right) + F_2 \sum \left(Q_{i\,Right} \,.\, x_i\right) = \left(\frac{q_1 + q_2}{2}\right) B \; B_i . \left[\frac{(2q_2 + q_1)B}{3(q_1 + q_2)}\right] \tag{3.3}$$

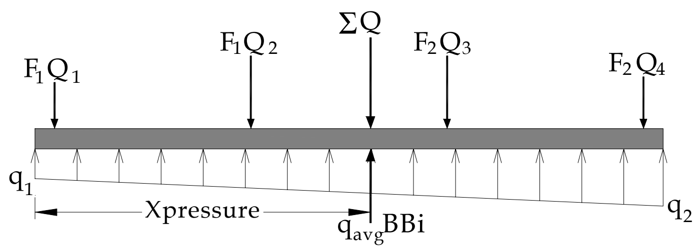

Figure (3.6): Layout of strip (Q1 Q2 Q3 Q4)- Second solution

From the above equations (3.2) and (3.3), the value of F_1 and F_2 can easily be obtained. As a result the shear force and bending moment diagrams can easily be constructed. Once again the researcher presents numerical values of the analysis of strip BDKM available within this paragraph. The detailed solution of mat as a whole using this method is also provided in appendix A.

The column loads on the strip BDKM and soil pressure under the mat strip are shown in the Figure (3.2)

$$\sum F_y = 0.0$$

$$F_1 \sum Q_{Left} + F_2 \sum Q_{Right} = \left(\frac{q_1 + q_2}{2}\right) B_i \; B$$

$$F_1(320.2+646.2)+F_2(560.8+255)=\left(\frac{16.06+13.12}{2}\right)*5*22.4$$

$$966.4\,F_1+815.8\,F_2=1{,}634.09\ ton$$

$$\sum M_{at\ left\ point}=0.0$$

$$F_1\sum(Q_{i\,Left}\cdot x_i)+F_2\sum(Q_{i\,Right}\cdot x_i)=\left(\frac{q_1+q_2}{2}\right)B\,B_i\cdot\left[\frac{(2q_2+q_1)B}{3(q_1+q_2)}\right] \qquad \ldots\ldots.(a1)$$

$$F_1(320.2(0.7)+646.2(7.7))+F_2(560.8(14.7)+255(21.7))=1{,}634.09\left(\frac{(2(13.12)+16.06)22.4}{3(16.06+13.12)}\right)$$

$$5{,}199.88F_1+13{,}777.26F_2=18{,}916.47 \qquad \ldots\ldots(b1)$$

By solving equations (a1) and (b1) for F_1 and F_2, give F_1 = 0.891 and F_2 = 0.948, therefore; the modified column numerical loads are as follows:

$Q_{1\ mod} = F_1\ Q_1 = 0.891*320.2 = 285.28$ ton

$Q_{2\ mod} = F_1\ Q_2 = 0.891*646.2 = 575.73$ ton

$Q_{3\ mod} = F_2\ Q_3 = 0.948*560.8 = 531.44$ ton

$Q_{4\ mod} = F_2\ Q_4 = 0.948*255 = 241.65$ ton

The soil pressure and modified column loads for strip BDKM is shown in Figure (3.7).

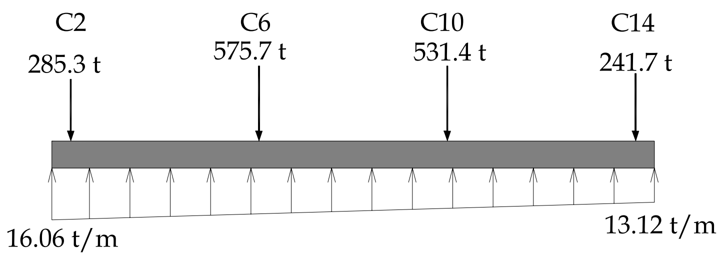

Figure (3.7): Loads on the strip BDKM after using the modification factors- second solution

The intensity of soil pressure under strip BDKM at distance x from the left of the strip is taken as $q_{ux}=16.06-0.131x$.

The shear force is obtained by integrating q_{ux} as follows:

$$V_{ux}=16.06\,x-\frac{0.131}{2}x^2+\text{Shear due to column loads}$$

The bending moment is obtained by integrating V_{ux} as follows :

$$M_{ux}=16.06\frac{x^2}{3}-\frac{0.131}{6}x^3+\text{Bending due to column loads}$$

The section of maximum bending moment corresponds to the section of zero shears, $V_u = 0.0$.

Table (3.2) and Figures (3.8) and (3.9) represent the shear and moment numerical values and the construction shape of shear force and the bending moment diagrams for strip BDKM.

Table (3.2): Shear and Moment numerical values for Strip BDKM-second solution

Strip BDKM

$B_2 =$ 5.00 m   B= 22.40 m

Column No.	Q'$_u$ (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	16.06	0.000			0.00
2	285.28			15.96	56.037	-229.243		19.63
		7	7.7				3.61	-312.17
6	575.73			15.05	313.489	-262.239		333.21
		7	14.7				11.24	-128.51
10	531.44			14.13	248.415	-283.021		303.53
		7	21.7				18.78	-270.49
14	241.65			13.22	195.555	-46.093		16.11
		0.7	22.4	13.12	0.000			0.00

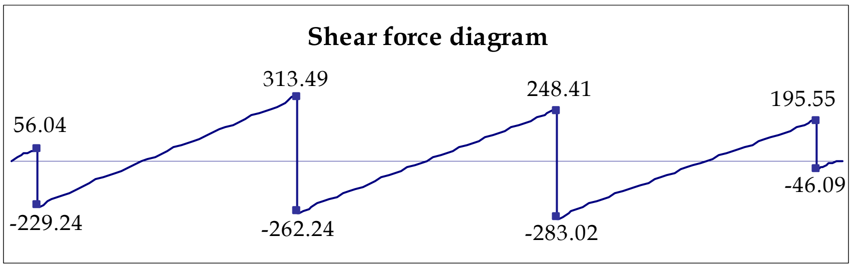

Figure (3.8): Shear force diagram for strip BDKM - Second solution

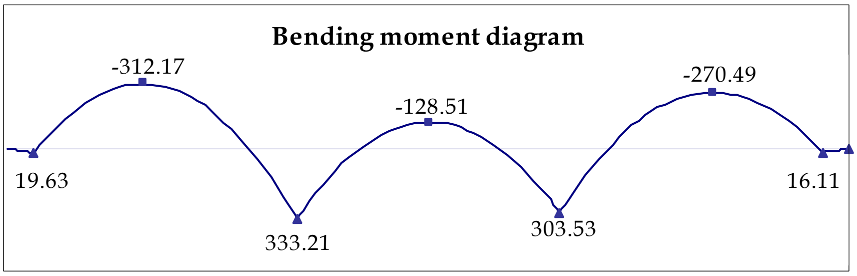

Figure (3.9): Moment diagram for strip BDKM - Second solution

3.2.3 Third Solution

This proposed solution will consider both the columns loads on the strip BDKM, and the applied soil pressure under the mat for the same strip at once, this strip will be modified by finding the average loads and factors for the applied column loads to make the value of the resultant of column loads equal and coincide with that of the average loads and factors for the applied soil pressure under the strip in addition to putting together the resultant of the soil reaction equal and coincide with the average applied column loads where the influence point for the average column load is at mid point between the influence points of column loads and soil reaction before applying the modifications factors. Two factors will be applied to make the resultant of the modified column load equal and coincide with the average loads, the first factor will be multiplied with the columns loads on the left side of the resultant of the modified column loads while the second factor will be multiplied by the columns loads on the right side of the resultant of modified column loads then finding the values of the maximum and minimum pressure under the studied strip at both ends. The constructed shear force and bending moment diagrams can then be easily sketched. The following are the symbolic analysis in terms of simple steps to help in understanding the proposed third solution (see Figure 3.10).

The mathematical equations can be represented as follows:

$$Q_{total} = \sum Q_i$$

$$Soil\ reaction\ (q_{avg} B_i\ B) = \left(\frac{q_1 + q_2}{2}\right) B_i\ \ B \qquad (3.4)$$

$$Average\,load = \frac{Q_{total} + q_{avg} B_i\ B}{2} \qquad (3.5)$$

$$x_{average} = \frac{x_l + x_p}{2} \qquad (3.6)$$

Where :

x_l is the distance between the Q_{total} and the left edge of mat strip

x_p is the distance between average soil pressure and the left edge of mat strip

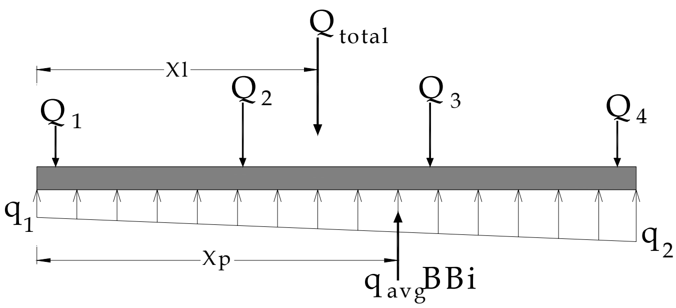

Figure (3.10): Applied loads on strip BDKM before the using the modification factors-Third solution

For modified columns load

$$\sum F_y = 0.0$$

$$F_1 \sum Q_{Left} + F_2 \sum Q_{Right} = \textit{Average load} \qquad (3.7)$$

$$\sum M_{\text{at left point}} = 0.0$$

$$F_1 \sum (Q_{i\,Left} \,.\, x_i) + F_2 \sum (Q_{i\,Right} \,.\, x_i) = \textit{Average load}.\ x_{average} \qquad (3.8)$$

Equations (4.7) and (4.8), gives F_1 and F_2.

Use equation (4.9) for modifying soil pressure

$$\left(\frac{q_{1,mod} + q_{2,mod}}{2}\right) B_i\ B = \textit{average load} \qquad (3.9)$$

where,

The centroid of the trapezoidal pressure for soil is

$$\left(\frac{(2q_{1,mod} + q_{2,mod})B}{3(q_{1,mod} + q_{2,mod})}\right) = x_{average} \qquad (3.10)$$

Equations (3.9) and (3.10), give $q_{1,mod}$ and $q_{2,mod}$

The modified soil pressure and column modification loads for the strip B D K M are shown in Figure (3.11)

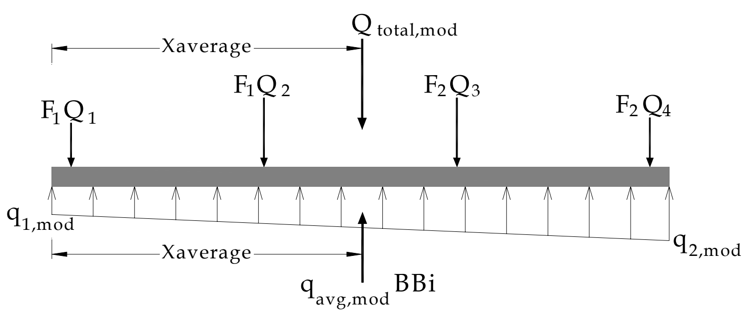

Figure (3.11): Applied loads on the strip BDKM after using the modification factors-Third solution

The complete design analysis using the proposed third solution for mat for the other strips is can also be found in the last part of appendix A.

The column loads on the strip BDKM and soil pressure from mat under the strip can be seen in the Figure (3.2).

$$Q_{total} = \sum Q_i = 1{,}782.2 \ \ ton$$

$$Soil\ reaction\,(q_{avg} B_i B) = \left(\frac{16.06+13.12}{2}\right) * 5 * 22.4 = 1{,}634.09\ ton$$

$$Average\,load = \frac{1{,}634.09+1{,}782.2}{2} = 1{,}708.15\,ton$$

$$x_L = 10.65\,m \ \ and \ \ x_p = 10.82\,m,$$

$$so, x_{average} = \frac{10.65+10.82}{2} = 10.74\,m$$

$$\sum F_y = 0.0$$

$$F_1 \sum Q_{Left} + F_2 \sum Q_{Right} = Average\,load$$

$$F_1(320.2+646.2) + F_2(560.8+255) = 1{,}708.15$$

$$966.4 F_1 + 815.8 F_2 = 1{,}708.15\ ton \qquad \text{.......(a2)}$$

$$\sum M_{at\ left\ point} = 0.0$$

$$F_1 \sum (Q_{i\,Left} \cdot x_i) + F_2 \sum (Q_{i\,Right} \cdot x_i) = Average\,load \cdot x_{average}$$

$$F_1(320.2*0.7+646.2*7.7) + F_2(560.8*14.7+255*21.7) = 1{,}708.15*10.74$$

$$5{,}199.88\,F_1 + 13{,}777.26\,F_2 = 18{,}345.53 \quad t.m \qquad \text{.......(b2)}$$

By solving equations (a2) and (b2) for F_1 and F_2, give F_1 = 0.945 and F_2 = 0.975, so the modified column loads are as follows:

$Q_{1\ mod} = F_1\ Q_1$ = 0.945*320.2 = 302.55 ton

$Q_{2\ mod} = F_1\ Q_2$ = 0.945*646.2 = 610.58 ton

$Q_{3\ mod} = F_2\ Q_3$ = 0.975*560.8 = 546.51 ton

$Q_{4\ mod} = F_2\ Q_4$ = 0.975*255 = 248.50 ton

$$\left(\frac{q_{1,mod}+q_{2,mod}}{2}\right) B_i\ B = average\ load$$

$$\left(\frac{q_{1,mod}+q_{2,mod}}{2}\right) * 22.4 * 5 = 1{,}708.15 \qquad \Rightarrow \quad (q_{1,mod}+q_{2,mod}) = 30.50$$

where

$$\left(\frac{\left(2\,q_{2,\mathrm{mod}}+q_{1,\mathrm{mod}}\right)B}{3\left(q_{1,\mathrm{mod}}+q_{2,\mathrm{mod}}\right)}\right)=x_{average}=10.74 \;\Rightarrow\; \frac{\left(q_{2,\mathrm{mod}}+30.50\right)22.4}{3\,(30.50)}=10.74$$

$q_{2,\mathrm{mod}}=13.36\;\; t/m^2$, *and*

$q_{1,\mathrm{mod}}=17.14\;\; t/m^2$

The modified soil pressure and modified column loads for the strip BDKM are shown in Figure (3.12).

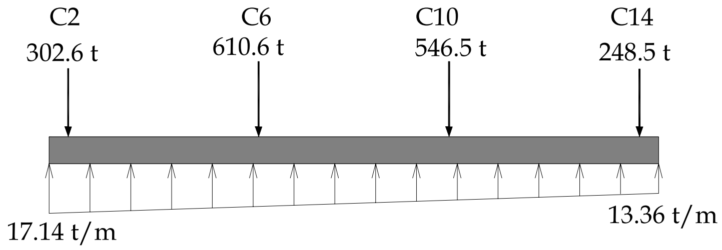

Figure (3.12): Applied load on the strip B D K M after using the modification factors- Third solution

The intensity of soil pressure under the strip BDKM at distance x from the left edge of the strip is $q_{ux}=17.14-0.169x$.

The shear force is obtained by integrating q_{ux} as follows:

$$V_{ux}=17.14\,x-\frac{0.169}{2}x^2+\text{Shear due to column loads}$$

The bending moment is obtained by integrating V_{ux} as follows:

$$M_{ux}=17.14\frac{x^2}{3}-\frac{0.169}{6}x^3+\text{Bending due to column loads}$$

The section of maximum bending moment corresponds to the section of zero shears, $V_u=0.0$

Table (3.3) represents the shear and moment numerical values and Figures (3.13) and (3.14) represent the shape of the construction shear force and bending moment diagrams for the strip BDKM.

Table (3.3): Shear and Moment numerical values for Strip BDKM -Third solution

Strip BDKM

$B_2 =$ 5.00 m   B = 22.40 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m²)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	17.14	0.000			0.00
2	302.55			17.03	59.800	-242.752		20.95
		7	7.7				3.59	-328.48
6	610.58			15.84	332.467	-278.117		359.12
		7	14.7				11.28	-135.37
10	546.51			14.66	255.679	-290.830		304.75
		7	21.7				18.76	-281.34
14	248.50			13.48	201.543	-46.959		16.41
		0.7	22.4	13.36	0.000			0.00

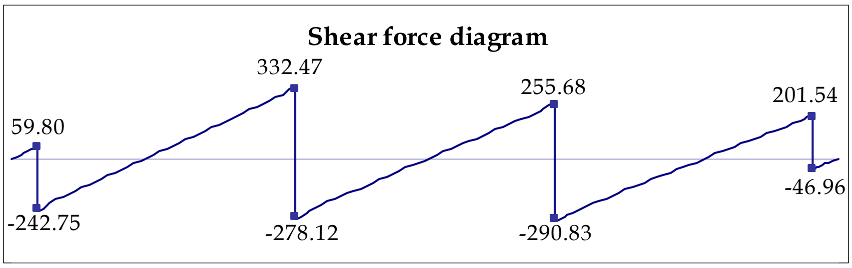

Figure (3.13): Shear force diagram for strip B D K M -Third solution

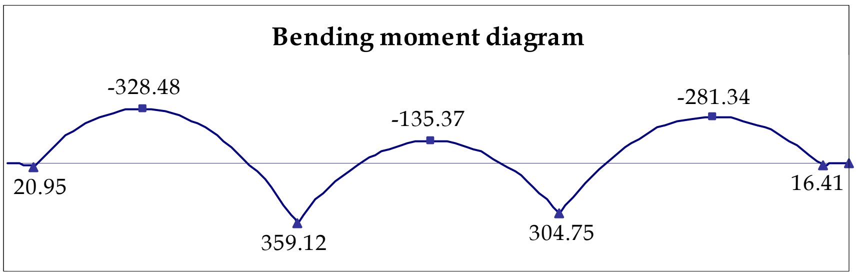

Figure (3.14): Moment diagram for strip B D K M -Third solution

From the analysis it has been noticed that the third suggested solution represents the average solution of both first and second suggested solutions approach for mat analysis mentioned earlier by the researcher in chapter 3, it can be seen that the numerical values of both bending moment and shear force obtained by the third solution lies between the upper and the lower bound numerical values obtained by the other two solutions, the upper bound values of the first column of Table (3.4) represents the first suggested solution of mat analysis while the lower bound values in the same column represent the second solution of mat suggested by the researcher and by observing the values obtained by the third solution it is clear evidence that those values correspond to an average of upper and lower bounds this is because in the third solution the column modified loads are taken between the first solution and the second solution for both modified applied column loads and applied soil pressure as suggested in that method for mat analysis (refer to section 3.2.3).

Table (3.4): Numerical moment values for Strip BDKM for the suggested three solutions

Solution	**Exterior Span (t.m)**		**Interior Span (t.m)**			**Exterior Span (t.m)**	
	Exterior + ve	**Interior - ve**	**Interior + ve**	**Interior - ve**	**Interior + ve**	**Interior - ve**	**Exterior + ve**
1st solution	22.31	344.99	385.98	142.45	304.88	292.10	16.67
2nd solution	19.63	312.17	333.21	128.51	303.53	270.49	16.11
3rd solution	20.95	328.48	359.12	135.37	304.75	281.34	16.41

Figure (3.15) characterizes the graphical representations for the three solutions collectively suggested by the researcher for the moment numerical values for strip BDKM.

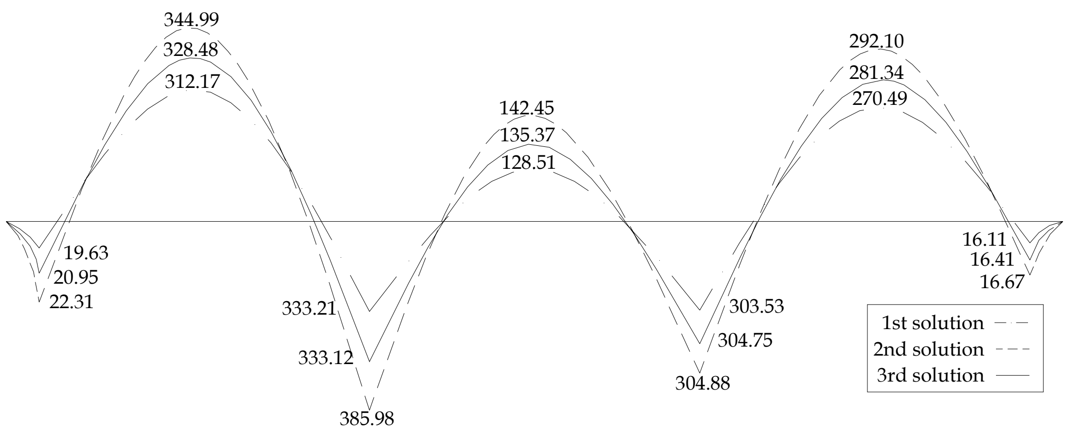

Figure (3.15) Graphical representations for the suggested three solutions collectively for the moment numerical values of strip BDKM.

Also, the value of shear force in third solution is roughly equal the average value between the values of the obtained shear force due to the first and the second solutions suggested by the researcher.

Table (3.5) summarizes the values of three solutions for shear force diagram for the strip BDKM and Figure (3.16) describes the graphical representations for the three solutions collectively suggested by the researcher for the shear numerical values for the strip BDKM.

Table (3.5): Numerical shear values for Strip BDKM for the suggested three solutions

Solution	Column No. 2		Column No. 6		Column No. 10		Column No. 14	
	Left	Right	Left	Right	Left	Right	Left	Right
1st solution	63.67	256.53	351.86	294.34	262.6	298.2	207.28	47.72
2nd solution	56.04	229.24	313.49	262.24	248.41	283.02	195.55	46.09
3rd solution	59.80	242.75	332.47	278.12	255.68	290.83	201.54	46.96

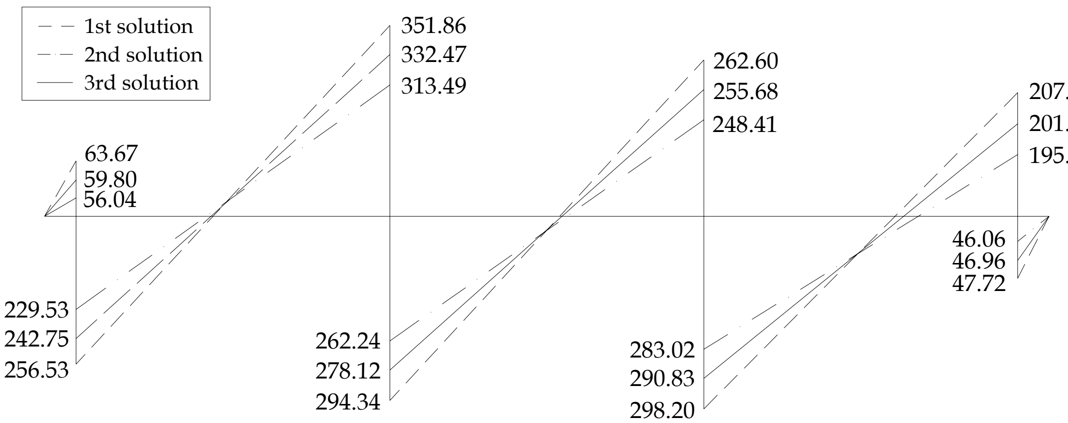

Figure (3.16): Graphical representations for the suggested three solutions collectively for the shear numerical values of strip BDKM.

Another L-shaped mat design analysis was worked-out to verify the validity of the third suggested solution proposed by the researcher established successfully for the rectangular mat shown in Figure (2.7). The L-shaped mat layout and the applied columns loads can be seen in Figure (3.17) and a comprehensive design analysis for all that strips are reachable in the end of the appendix B.

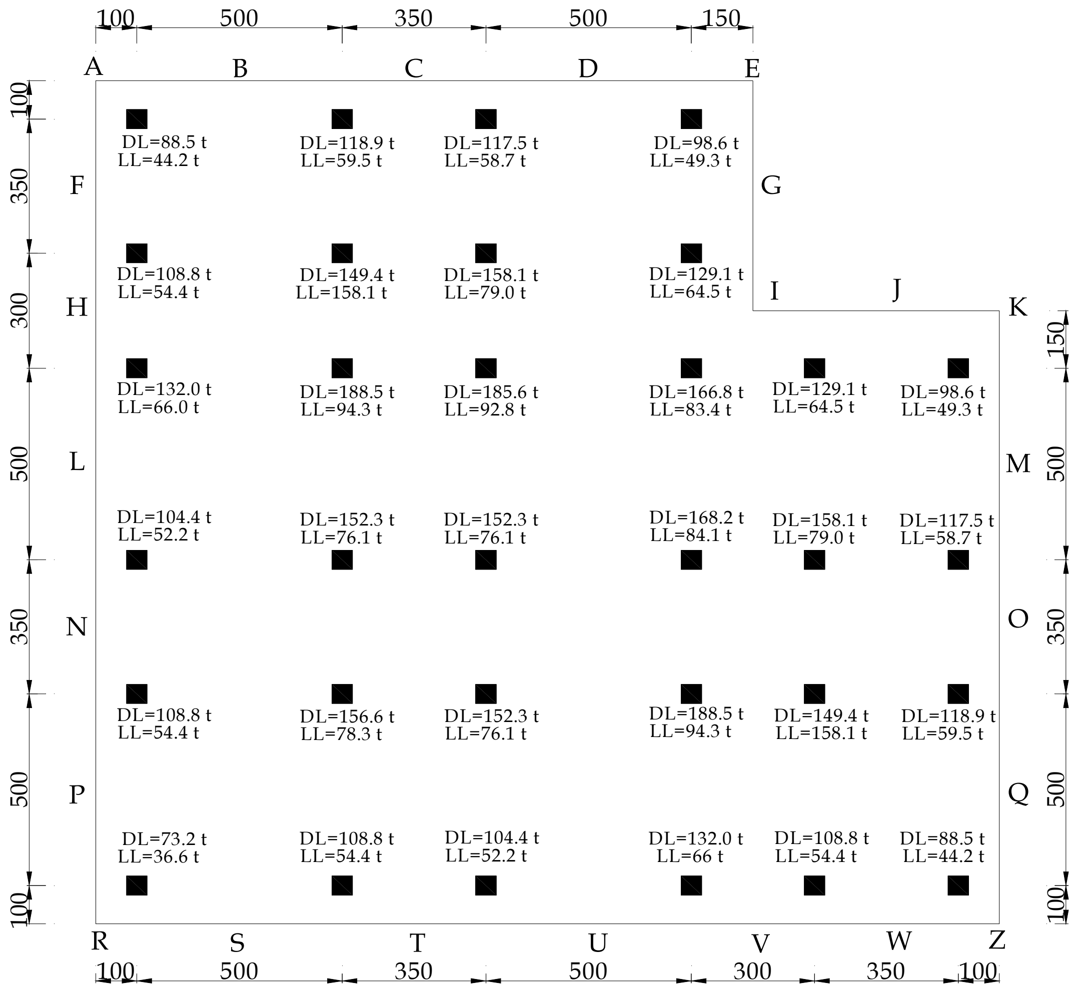

Figure (3.17): Layout of L-shaped mat foundation and columns loads

According to the design analysis performed on the mat L shape using the suggested third solution by finding the average loads and factors for the applied column loads to create the value of the resultant of column loads equal and correspond with that of the average loads and factors for the applied soil pressure under the strip furthermore to putting together the resultant of the soil reaction equal and coincide with the average load where the influence point for the average load is at mid point between the influence points of column loads and soil reaction before applying the modifications factors it was clear evidence that the method suggested by the researcher is also valid for L-shaped mat.

In conclusion, the researcher recommends the third solution takes into account both the modifications for the column load and the modification for the applied soil pressure as a reasonable solution however the researcher will construct a finite element model to analyze mat foundation using a number of available commercial software and compare the obtained results from them to the solutions proposed for the conventional rigid method in this thesis as will be shown later in chapter 5.

3.4 Computer Program

A user friendly computer structural analysis program was developed by the researcher to analyze mat foundation strips using the proposed optimum average solution (third solution) discussed in section 3.3.3 by the researcher.

The programming language used to develop this software was based on Microsoft C# (sharp) . NET and a copy of the developed software is attached at the back page cover of the thesis. Also the program is equipped with a help menu contains the analysis of mat shown in Figure (2.7) and other examples of a real mat foundation and their applied loads for some multi story building to work as a tutorials to help potential users to use easily this developed software by the researcher. This program prompts the user to enter first the distance from the left edge of mat boarders to the left columns and to enter the distance from right edge of mat boarders to the right columns of mat followed by entering the top distance between top mat boarders and the top columns and entering the distance between bottom mat boarders and bottom columns. Also the user needs to feed the program with the number of spans and the spans length in both directions. Another advantage of the program is that the built in functions are so flexible that the user has the ability to modify the length of spans input, the number of spans enter and modify the load applied column. As soon as the input is final, the program divides the mat into a number of strips, each of these strips only carry half of the distance between columns, then the program displays the mat layout and dimensions and the column applied load and the applied soil pressure before and after modification for the selected strip and finally the program does the analysis and design internally based on the researcher average modified solution to be ready for display the final output. Shortly as the user picked up the mat strip, the shape and the values of both shear force and bending moment diagrams are easily can be displayed.

A complete mat foundation analysis of Figure (2.7) in chapter 2 was worked out by the researcher by using the developed computer program software and showed exact results to those values obtained both by hand calculations and by the developed optimized excel sheet. The following display screens of Figure (3.18) and Figure (3.19) show the mat layout strips and the applied column load and the applied modified pressure after modification respectively, in addition to the output of the analysis of both the shear force and the bending moment diagrams of strip B D K M as can be seen in Figure (3.20) and Figure (3.21) correspondingly.

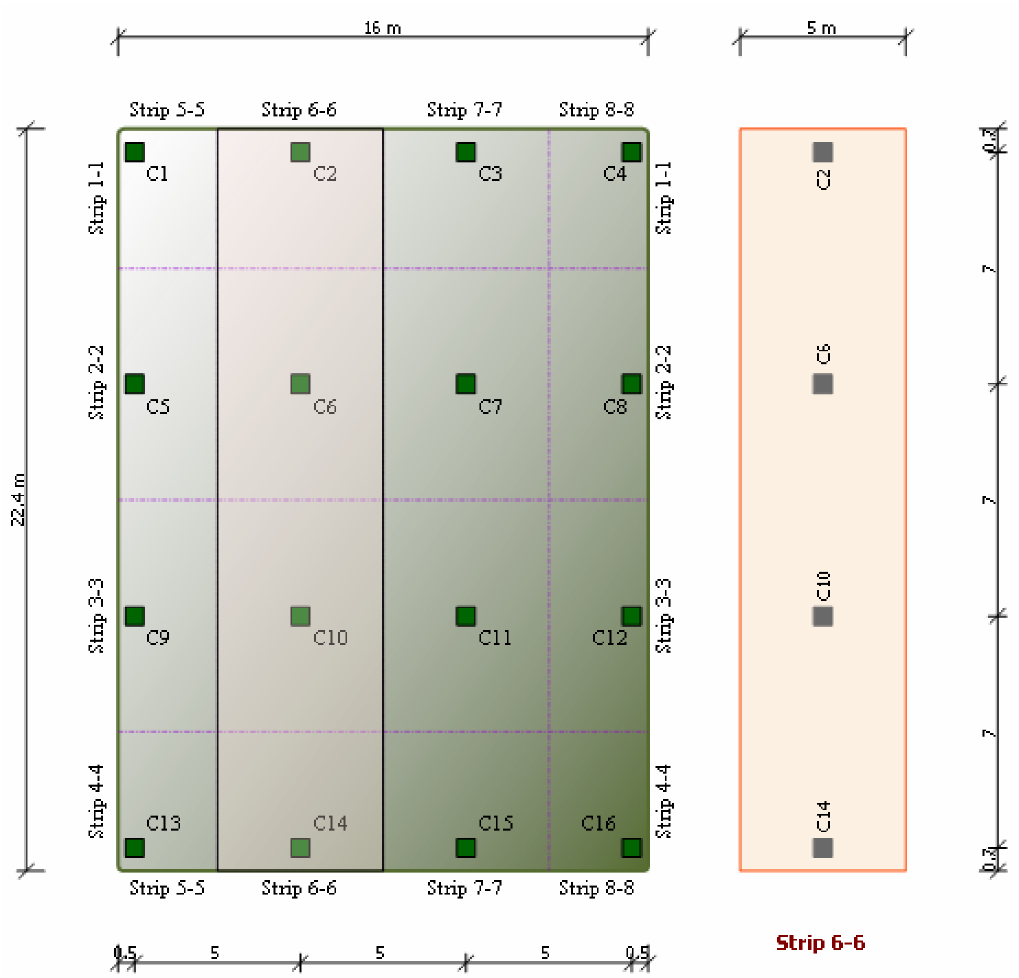

Figure (3.18): Mat layout produced by the developed computer program

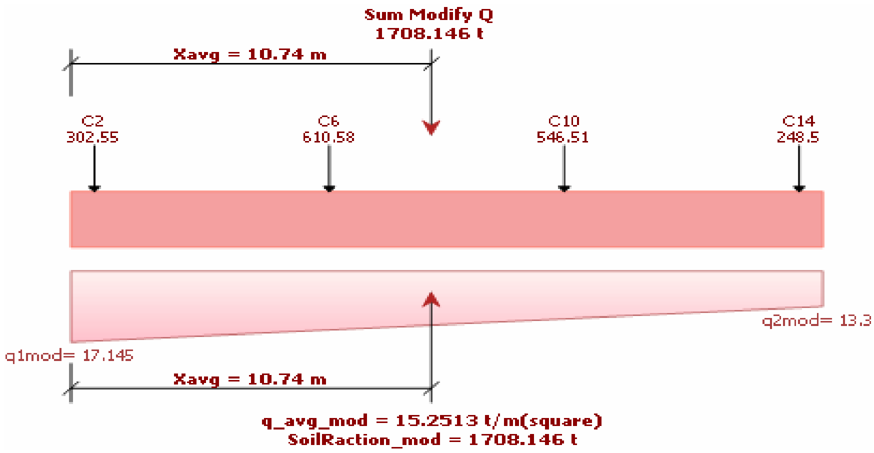

Figure (3.19): Applied columns load and soil pressure after modifications

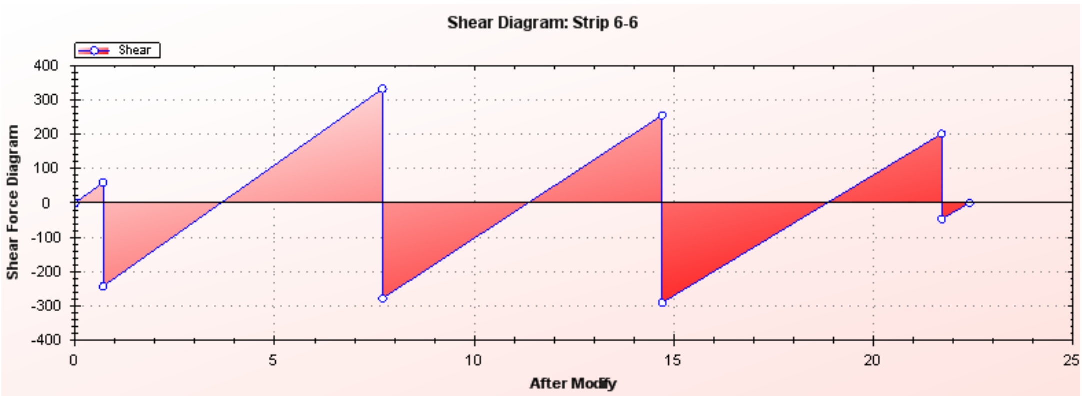

Figure (3.20): Shear force diagram screen display by the use of computer program

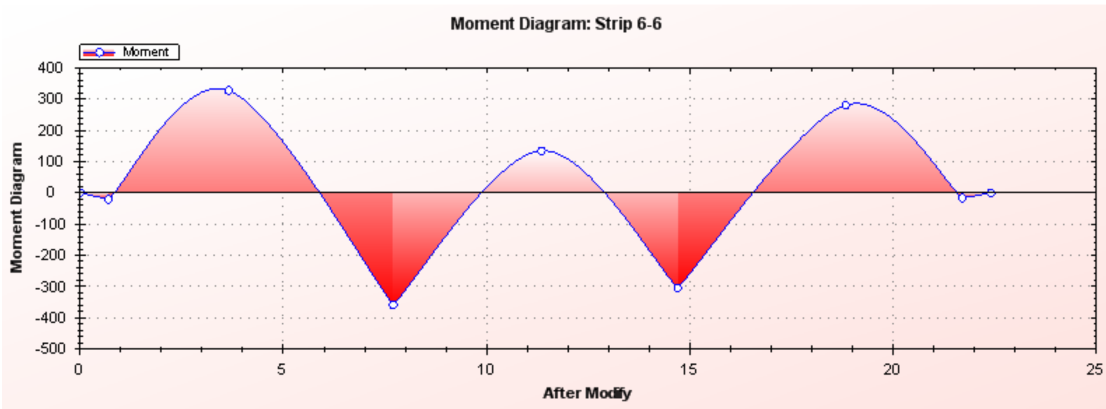

Figure (3.21): Bending moment diagram screen display by the use of computer program

The following chapter will be an experimental testing for a number of selected sand sites to get the subgrade reactions numerical values in addition to analysis of a number of old plate load tests on sandy soil performed by material and soil laboratory of Islamic University of Gaza to be used later in chapter 5 for more exact and accurate analysis.

Chapter 4

Field Plate Load Test Set Up on Sandy Soil

4.1 Introduction

This chapter contains a detailed description of the field plate load test of a sandy soil and how to determine the coefficient of subgrade reaction. The experimental output will assist the researcher to use real numerical values of subgrade reactions of a sandy soil for a site to be employed later in the finite element modeling, using the flexible method of mat foundation as will be discussed in chapter 5. In addition it includes a comprehensive analysis for a number of reports of old plate load tests experiments done by material and soil laboratory of Islamic University of Gaza on sandy soil to produce a relation to calculate the coefficient of subgrade reactions K of sandy soil as a function of known settlement and compare it to the Bowels relation (1997).

4.2 Site Information

The plate load test was used to determine the subgrad reactions on top of a deep layer of yellow natural sandy soil on a site located to the west of Dair-Albalah area in Gaza strip, a 150 meter a way from the Mediterranean Sea. The site was excavated by a bulldozer at 30 cm under the surface level.

4.3 Field Plate Load Test Set Up

The plate load test is a field test performed on uniform sandy and clayey soils. In this thesis, the researcher will only conduct the test on a number of sites of sandy soil. This will help in determining the possible settlement of the soil for a given loading and at a given depth to determine the subgrade reaction for the soil and the ultimate bearing capacity. Three tests have been performed to get the subgrade reactions, two of them using plate size of 30 cm and a thickness of 2.5 cm while the third test used steel plate of 45 cm and a thickness of 2.5 cm. The load on the plate was applied by making use of a hydraulic jack of 50 tons capacity and capable to measure 0.2 tones. The reaction of the jack load was taken as the weight of the bulldozer to give a reaction of minimum 15 tons as shown in Figure (4.1). The settlement of the plate was measured by a set of three dial gauges of 50mm travel of sensitivity 0.01 mm. The dial gauges were fixed to two reference steel beams 2.5 meter long which were not disturbed during the test. The test was carried at 0.3 m under the surface level and according to ASTM D1194-94 standard.

Figure (4.1): Arrangement for plate load test set-up

4.4 Test procedures using 30 cm and 45 cm diameter plates

Step by step summary of the field experiment of plate load of 30 cm and 45 cm tests is listed below:

1. The plate is placed at 0.3 m under the surface level, then the soil below the plate was leveled.
2. The plate was centered below the center of gravity of the bulldozer. Then the hydraulic jack was located on the center of the plate.
3. Two long reference steel beams 2.5 m long were fixed firmly beside the plate and three dial gauges were attached firmly to the beams. The dial gauges were distributed equally on the plate.
4. Initial dial reading was recorded.
5. The soil at that level was kept at its normal moisture content up to allowable load.

6. The 45 cm plate was loaded in equal increments of about 2 ton while the 30 cm plate was loaded of 0.8 ton, increment.
7. The time interval between each load increment was 15 minutes as the settlement was ceased or its rate is very low. The settlement was recorded for each load increment.
8. The load was increased up to about three times the predictable allowable bearing capacity.
9. Load versus settlement records for the 30 cm plate performed on two different spots on the same construction site are summarized in Tables (4.1) and (4.2). The test plots correspond to load versus settlement for 30 cm plate are shown in Figures (4.2) and (4.3), in addition, Figure (4.4) signifies the curve fitting for the two different tested samples on the same construction site using a 30 cm plate.
10. Load versus settlement records for the 45 cm plate was carried out on the same construction site is summarized in Tables (4.3). The tests plot correspond to load versus settlement for the 45 cm plate is shown in Figure (4.5).

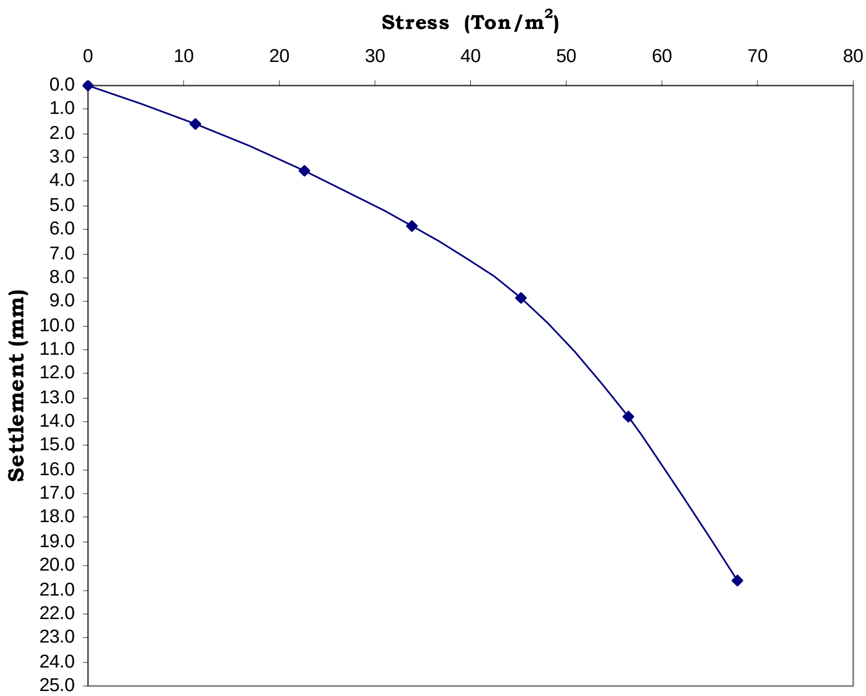

Figure (4.2): Load versus settlement of 30 cm plate load test (first test)

Table (4.1): An experimental plate load test results obtained from three attached reading gauges for load versus settlement using 30 cm plate (first test)

Loading Stages	ELAPSED time (min)	LOAD (ton)	STRESS ton/m^2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVERAGE (mm)
				G_1	G_2	G_3	S_1	S_2	S_3	
Initial Load Reading	0.00	0	0	28.86	37.71	45.66	0.00	0.00	0.00	***0.00***
	0.00	0.8	11.31	27.94	36.74	44.23	0.92	0.97	1.43	**1.11**
	5.00			27.59	36.39	43.84	1.27	1.32	1.82	**1.47**
	10.00			27.51	36.18	43.71	1.35	1.53	1.95	**1.61**
	15.00			27.50	36.16	43.68	1.36	1.55	1.98	**1.63**
	0.00	1.6	22.63	26.25	34.83	42.04	2.61	2.88	3.62	**3.04**
	5.00			25.87	34.52	41.67	2.99	3.19	3.99	**3.39**
	10.00			25.79	34.42	41.48	3.07	3.29	4.18	**3.51**
	15.00			25.78	34.41	41.44	3.08	3.30	4.22	**3.53**
	0.00	2.4	33.94	24.19	32.64	39.25	4.67	5.07	6.41	**5.38**
	5.00			23.94	32.33	38.90	4.92	5.38	6.76	**5.69**
	10.00			23.87	32.23	38.67	4.99	5.48	6.99	**5.82**
	15.00			23.86	32.22	38.64	5.00	5.49	7.02	**5.84**
	0.00	3.2	45.25	22.41	30.64	36.45	6.45	7.07	9.21	**7.58**
	5.00			21.91	29.93	35.42	6.95	7.78	10.24	**8.32**
	10.00			21.66	29.59	34.77	7.20	8.12	10.89	**8.74**
	15.00			21.61	29.51	34.63	7.25	8.20	11.03	**8.83**
	0.00	4	56.57	19.36	26.79	31.07	9.50	10.92	14.59	**11.67**
	5.00			18.42	25.74	29.58	10.44	11.97	16.08	**12.83**
	10.00			17.98	25.06	28.73	10.88	12.65	16.93	**13.49**
	15.00			17.71	24.77	28.31	11.15	12.94	17.35	**13.81**
	0.00	4.8	67.88	16.09	21.23	22.64	12.77	16.48	23.02	**17.42**
	5.00			14.58	19.59	19.91	14.28	18.12	25.75	**19.38**
	10.00			13.91	18.87	18.69	14.95	18.84	26.97	**20.25**
	15.00			13.62	18.52	18.18	15.24	19.19	27.48	**20.64**
	0.00	5.6	79.19	Continuous Settlement						
	5.00									
	10.00									
	15.00									

Table (4.2): An experimental plate load test results obtained from three attached reading gauges for load versus settlement using 30 cm plate (second test)

Loading Stages	ELAPSED time (min)	LOAD (ton)	STRESS ton/m^2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVERAGE (mm)
				G_1	G_2	G_3	S_1	S_2	S_3	
Initial Load Reading	0.00	0	0	35.27	46.77	35.92	0.00	0.00	0.00	***0.00***
	0.00	0.8	11.31	33.79	45.16	35.02	1.48	1.61	0.90	**1.33**
	5.00			33.27	44.65	34.74	2.00	2.12	1.18	**1.77**
	10.00			33.09	44.37	34.65	2.18	2.40	1.27	**1.95**
	15.00			33.06	44.37	34.64	2.21	2.40	1.28	**1.96**
	0.00	1.6	22.63	32.38	43.33	34.63	2.89	3.44	1.29	**2.54**
	5.00			31.61	42.34	34.08	3.66	4.43	1.84	**3.31**
	10.00			31.34	41.92	33.93	3.93	4.85	1.99	**3.59**
	15.00			31.32	41.84	33.91	3.95	4.93	2.01	**3.63**
	0.00	2.4	33.94	29.64	39.65	32.67	5.63	7.12	3.25	**5.33**
	5.00			28.86	38.68	32.11	6.41	8.09	3.81	**6.10**
	10.00			28.55	38.25	31.89	6.72	8.52	4.03	**6.42**
	15.00			28.51	38.18	31.87	6.76	8.59	4.05	**6.47**
	0.00	3.2	45.25	26.52	35.08	30.15	8.75	11.69	5.77	**8.74**
	5.00			25.73	33.88	29.46	9.54	12.89	6.46	**9.63**
	10.00			25.34	33.11	29.15	9.93	13.66	6.77	**10.12**
	15.00			25.22	32.90	29.07	10.05	13.87	6.85	**10.26**
	0.00	4	56.57	20.05	26.30	24.39	15.22	20.47	11.53	**15.74**
	5.00			17.93	23.55	22.44	17.34	23.22	13.48	**18.01**
	10.00			16.87	22.17	21.46	18.40	24.60	14.46	**19.15**
	15.00			16.64	21.84	21.29	18.63	24.93	14.63	**19.40**
	0.00	4.8	62.22	Continuous Settlement						
	5.00									
	10.00									
	15.00									

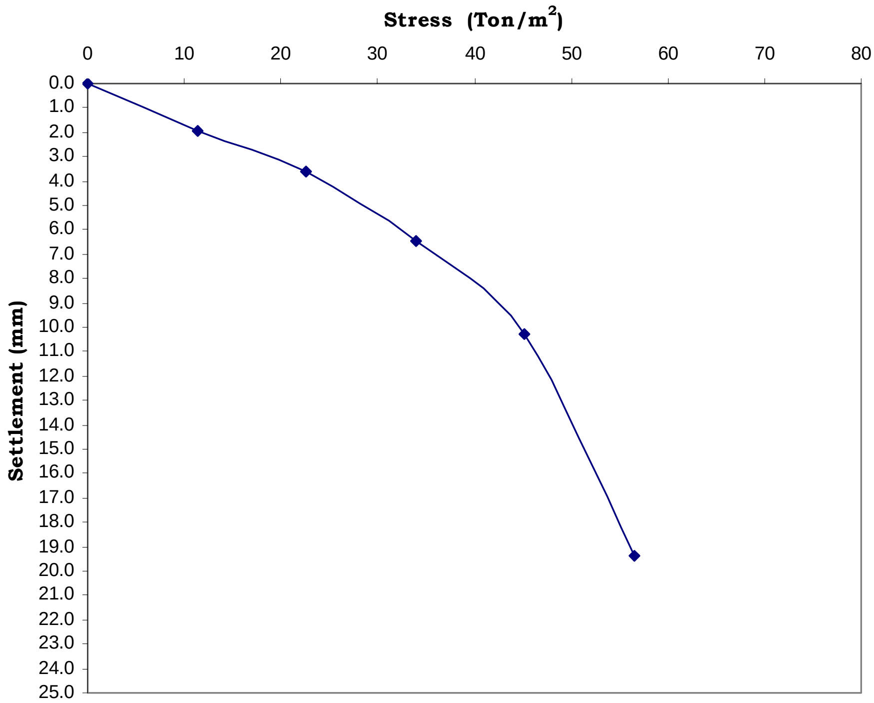

Figure (4.3): Load versus settlement of 30 cm plate load test (second test)

A fitting curve was initiated from the experimental results of the two different samples on the construction site that used same plate diameter of 30 cm to represent the final load versus settlement for the plate load test can be seen in Figure (4.4).

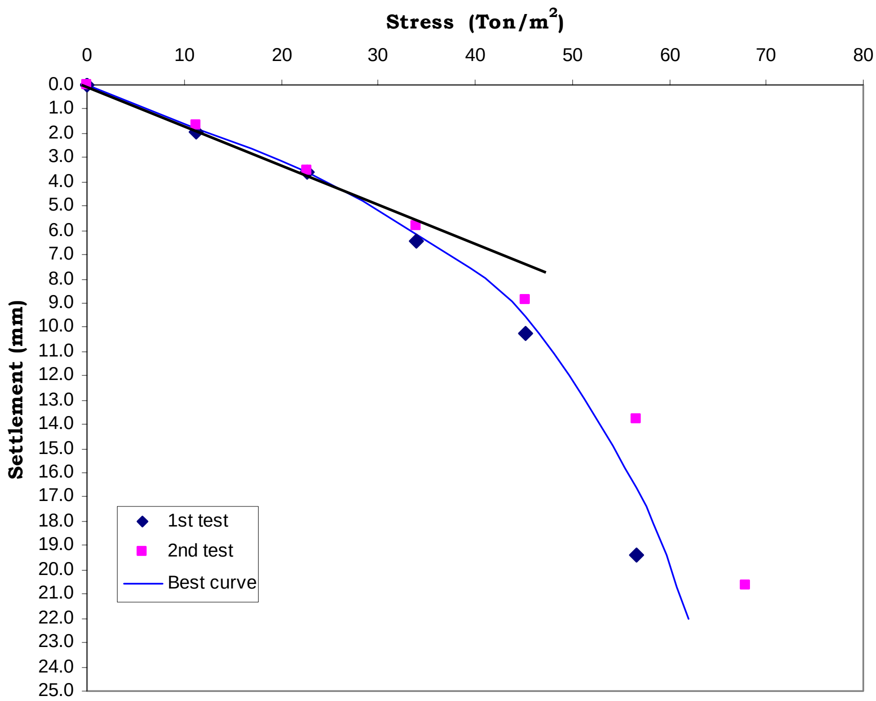

Figure (4.4): Fitting curve to represent final load versus settlement of 30 cm plate load test (first and second tests)

The subgrade reaction can be calculated for plate diameter of 30 cm by establishing a line that modify the fitting curve then finding the slope of this line as can be easily obtained from Figure (4.4). This represents the subgrade reactions K for the 30 cm plate as follows:

$$k_{0.3} = \frac{q}{\delta} = \frac{20\ (t/m^2)}{3.2\ (mm)} = 6250\ t/m^3$$

Where

$k_{0.3}$: Coefficient of subgrade reaction for 30 cm plate load tests

q : The soil pressure at a given point obtained graphically from Figure (4.4).

δ : the settlement of the plate at the same point.

As defined by Das (1999) the coefficient of subgrade reactions for sandy soils can be found as, $k_{BxB} = \mathrm{k}_{0.45}\left(\frac{B+0.3}{2B}\right)^2$ (4.1)

Where

k_{BxB} : Coefficient of subgrade reaction for square foundation (BxB)

B : Mat width obtained from Figure (2.7).

$$k_{BxB} = \mathrm{k}_{0.3}\left(\frac{B+0.3}{2B}\right)^2 \Rightarrow k_{16x16} = 6250\left(\frac{16+0.3}{2x16}\right)^2 = 6250(0.5094)^2 = 1622\,t/m^3$$

It is clear that the width of the mat is way bigger than the diameter of the plate and it is a reasonable assumption to assume that the diameter of the plate goes to zero and the above equation can be modified to the following form:

$$k_{BxB} = \mathrm{k}_{0.3}\left(\frac{B}{2B}\right)^2 = 0.25\,k_{0.3} \quad \text{That gives } k_{16x16} = 0.25 * 6250 = 1563\ \mathrm{t/m^3} \approx 1622\,t/m^3$$

For a rectangular foundation with length L and width B placed on sandy soil Das (1999) can be calculated as follows, $k_{\mathrm{LxB}} = \mathrm{k}\left(\frac{1+\mathrm{B/2L}}{1.5}\right)$ (4.2)

Where: k_{LxB} is the coefficient of subgrade reaction for rectangular foundation (LxB)

$$k_{\mathrm{LxB}} = \mathrm{k}\left(\frac{1+\mathrm{B/2L}}{1.5}\right)$$

$$k_{22.4x16} = 1622\left(\frac{1+0.5\dfrac{16}{22.4}}{1.5}\right) = 1468\,t/m^2$$

Table (4.3): An experimental plate load test results obtained from three attached reading gauges for load versus settlement using 45 cm plate

Loading Stages	ELAPSED time (min)	LOAD (ton)	STRESS ton/m^2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVERAGE (mm)
				G_1	G_2	G_3	S_1	S_2	S_3	
Initial Load Reading	0.00	0	0	27.15	34.88	31.50	0.00	0.00	0.00	***0.00***
	0.00	2	12.19	25.82	34.00	29.75	1.33	0.88	1.75	**1.32**
	5.00			25.58	33.56	29.43	1.57	1.32	2.07	**1.65**
	10.00			25.51	33.41	29.35	1.64	1.47	2.15	**1.75**
	15.00			25.49	33.28	29.27	1.66	1.60	2.23	**1.83**
	0.00	4	24.38	24.30	32.50	27.95	2.85	2.38	3.55	**2.93**
	5.00			24.00	32.21	27.50	3.15	2.67	4.00	**3.27**
	10.00			23.88	32.11	27.32	3.27	2.77	4.18	**3.41**
	15.00			23.84	32.09	27.24	3.31	2.79	4.26	**3.45**
	0.00	6	36.56	22.40	30.65	25.30	4.75	4.23	6.20	**5.06**
	5.00			21.72	30.20	24.67	5.43	4.68	6.83	**5.65**
	10.00			21.50	30.00	24.40	5.65	4.88	7.10	**5.88**
	15.00			21.43	29.92	24.33	5.72	4.96	7.17	**5.95**
	0.00	8	48.75	19.30	27.75	21.45	7.85	7.13	10.05	**8.34**
	5.00			18.40	26.90	20.30	8.75	7.98	11.20	**9.31**
	10.00			18.08	26.55	19.95	9.07	8.33	11.55	**9.65**
	15.00			17.98	26.43	19.85	9.17	8.45	11.65	**9.76**
	0.00	9	54.85	17.00	25.44	18.25	10.15	9.44	13.25	**10.95**
	5.00			15.95	24.40	17.10	11.20	10.48	14.40	**12.03**
	10.00			15.50	24.03	16.65	11.65	10.85	14.85	**12.45**
	15.00			15.38	23.92	16.49	11.77	10.96	15.01	**12.58**
	0.00	10	60.94	14.20	22.25	14.05	12.95	12.63	17.45	**14.34**
	5.00			12.45	20.33	12.28	14.70	14.55	19.22	**16.16**
	10.00			11.75	19.60	11.40	15.40	15.28	20.10	**16.93**
	15.00			11.52	19.39	11.11	15.63	15.49	20.39	**17.17**
	0.00	11.6	70.69	8.25	15.90	7.10	18.90	18.98	24.40	**20.76**
	5.00			6.50	14.00	4.60	20.65	20.88	26.90	**22.81**
	10.00			4.75	12.30	3.30	22.40	22.58	28.20	**24.39**
	15.00			3.50	11.10	2.00	23.65	23.78	29.50	**25.64**
	0.00	12	73.13	Continuous Settlement						
	5.00									
	10.00									
	15.00									

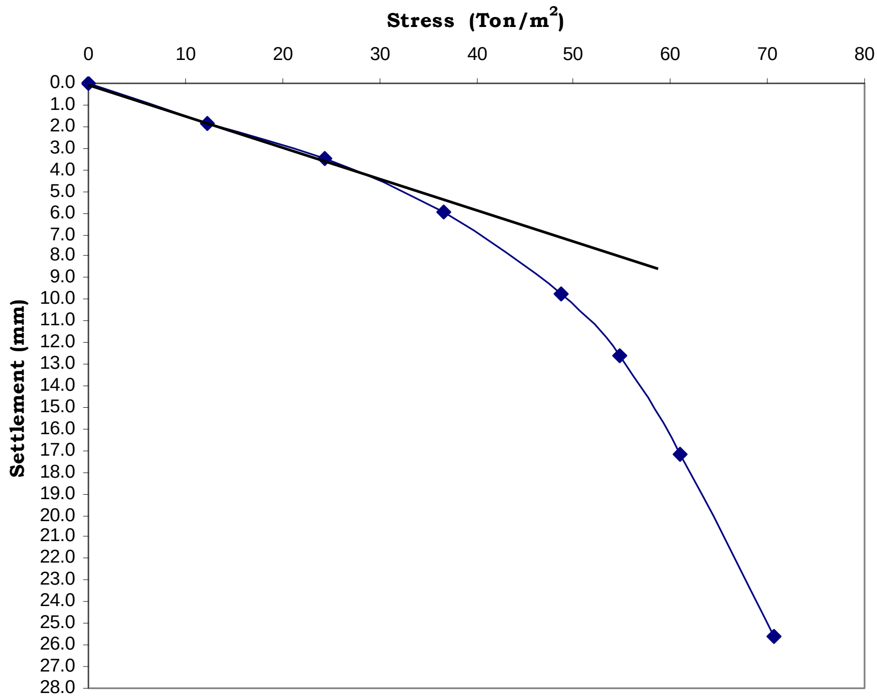

Figure (4.5) Fitting curve to represent load versus settlement of 45 cm plate load test

The subgrade reaction for plate 45 cm diameter can be found by drawing a straight line that modify the curve as shown in Figure (4.5) and finding the slope of that line which represent the subgrade reactions k for plate diameter of 45 cm as follows:

$$k_{0.45} = \frac{q}{\delta} = \frac{20\ (t/m^2)}{3.1(mm)} = 6452\ t/m^3$$

Where

$k_{0.45}$: Coefficient of subgrade reaction for 45 cm plate load tests

q : The soil pressure at a given point obtained graphically from Figure (4.5).

δ : the settlement of the plate at the same point.

As defined by Das (1999) the coefficient of subgrade reactions for sandy soils can be found as,

$$k_{BxB} = \mathrm{k}_{0.45}\left(\frac{B+0.45}{2B}\right)^2 \qquad (4.3)$$

Where:

k_{BxB} : Coefficient of subgrade reaction for square foundation (BxB)

B : Mat width obtained from Figure (2.7).

$$k_{BxB} = \mathrm{k}_{0.45}\left(\frac{B+0.45}{2B}\right)^2$$

$$k_{16x16} = 6452\left(\frac{16+0.45}{2*16}\right)^2 = 6452(0.5143)^2 = 1706\, t/m^3$$

Similarly as the diameter of the plat is very small when compared to the width of the mat it is assumed that the diameter of plate can be neglected as shown in the following relation:

$$k_{BxB} = \mathrm{k}_{0.45}\left(\frac{B}{2B}\right)^2 = 0.25\, k_{0.45} \quad \text{so,} \quad k_{BxB} = 0.25 * 6452 = 1613\ \mathrm{t/m^3} \approx 1706\, t/m^3$$

For rectangular mat foundation: L by B placed on sandy soil: $k_{\mathrm{LxB}} = \mathrm{k}_{\mathrm{BxB}}\left(\frac{1+\mathrm{B/2L}}{1.5}\right)$

Where k_{LxB} : Coefficient of subgrade reaction for rectangular foundation (LxB)

$$k_{22.4x16} = 1706\left(\frac{1+0.5\frac{16}{22.4}}{1.5}\right) = 1544 t/m^3$$

Based on the above calculations for the two computed values of the subgrade reactions it can be recommended that the value of the subgrade k is close to 1500 ton/m^3. The bearing capacity of the soil based on the plate load test was evaluated and was 14.9 t/m^2. The details of these calculations of the bearing capacity, the plate load test experiment report, and related plate load test photos can be found in appendix C.

4.5 Additional plate load tests reports

A number of plate load test on a sandy soil were conducted by the material and soil laboratory of Islamic University of Gaza on a number of locations within Tel Alsultan district in Rafah city, Gaza strip. Most of the results of plate load tests conducted by material and soil laboratory on the sandy soil showed that a bearing capacity of about 15 ton/m^2, it is essential to mention that these experiments were not conducted to find out the coefficient of subgrade reactions rather than to check out the values of the recommended bearing capacity. All of plate load tests reported on sandy soil were performed on the top layer at the above mentioned location; this layer was classified as deep yellow natural dune sand. The reports obtained by the material and soil laboratory of Islamic University of Gaza for Tel Alsultan, Rafah and the plate load test conducted by the researcher on sandy soil in Deir-Albalah were collected and divided into three separate groups as follows:

Group 1:

This group contains the plate load tests executed by the researcher with the help of the material and soil laboratory of Islamic University of Gaza on plate diameter of 30 cm as can be seen in Figure (4.2) and Figure (4.3) and from the two constructed figures the researcher was able to obtain the best fitted curve (the average settlement to the same stresses values, this means that the first curve represents the lowest values of the settlement while the second curve represents the largest values of the settlement) as was explained earlier in the section 4.3 and can be seen at Figure (4.4).

Group 2:

This group represents a collection of six plate load tests of diameter 45 cm performed on dune sandy soil on six random locations within lot 2 in Tel Alsultan area in Rafah city, Gaza strip. Figure (4.6) shows the graphical representations of stress versus settlement curve of the six plate load test samples.

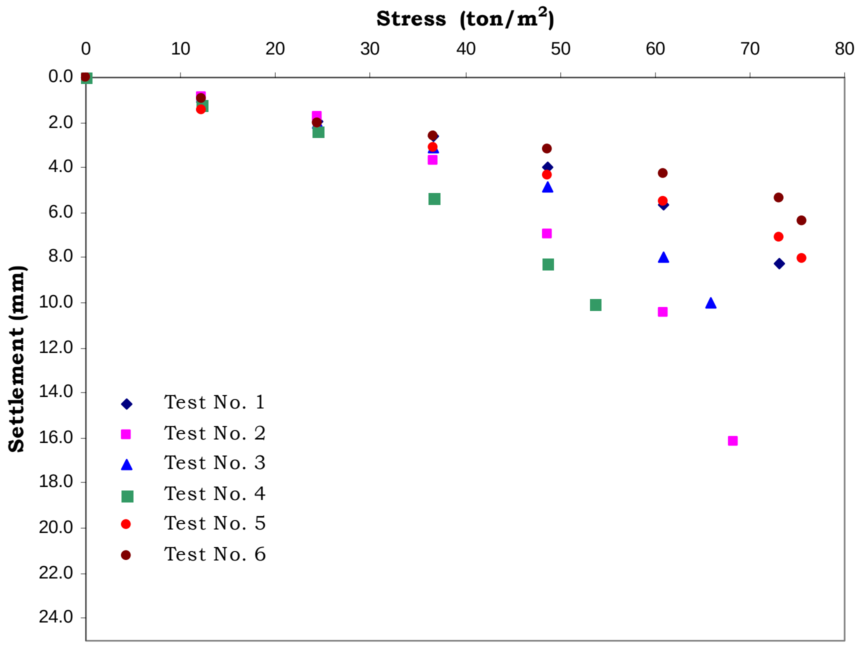

Figure (4.6): Stress versus settlement of 45 cm plate load test (Group 2)

By using Figure (4.6) the researcher constructed a lower bound curve closely to fit the lowest settlement values versus stresses and was named curve 1 as can be seen in Figure (4.6). On the other hand the researcher also constructed upper bound curve closely to fit the highest obtained values of settlement versus stresses and was named curve 2. From curve 1 and curve 2 shown in Figure (4.7), the researcher established the best fitting curve from the two curves to represent the average numerical settlement values versus the average stresses as can be seen in Figure (4.7). See Appendix C for more information related to the six experimental plate load test results. The best curve equation of Figure (4.7) was found as follows:

$$q_{u2\,(P)} = 15\ S_P - 0.74\ S_P^{\ 2} \tag{4.4}$$

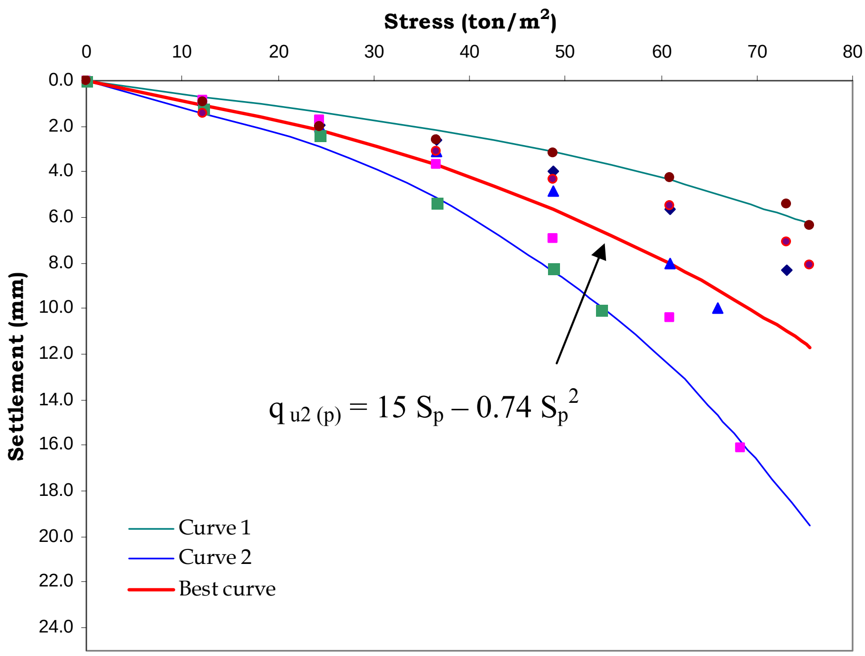

Figure (4.7): Best fitting curve to represent the average settlement values of 45 cm plate load test versus average stresses (Group 2)

Group 3:

This group describes five plate load tests of 45 cm carried out on lot 3 in Tel Alsultan area of Rafah city, Gaza strip. Similarly the five plate load tests samples have been represented graphically by the researcher as can be seen in Figure (4.8). Two curves have been established, the first is a lower bound curve to fit the lowest settlement values versus stresses and was named curve 1 as can be seen in Figure (4.9) and the other is an upper bound curve to fit the highest obtained values of settlement versus stresses and was named curve 2 shown in Figure (4.9). The best fitting curve from both curves to represent the average numerical settlement values versus the average stresses can be seen in Figure (4.9). See Appendix C for more information related to the five experimental plate load test results. The best curve equation of Figure (4.9) was found as follows:

$$q_{u3(P)} = 11.08\,S_P - 0.41\ S_P^{\ 2} \tag{4.5}$$

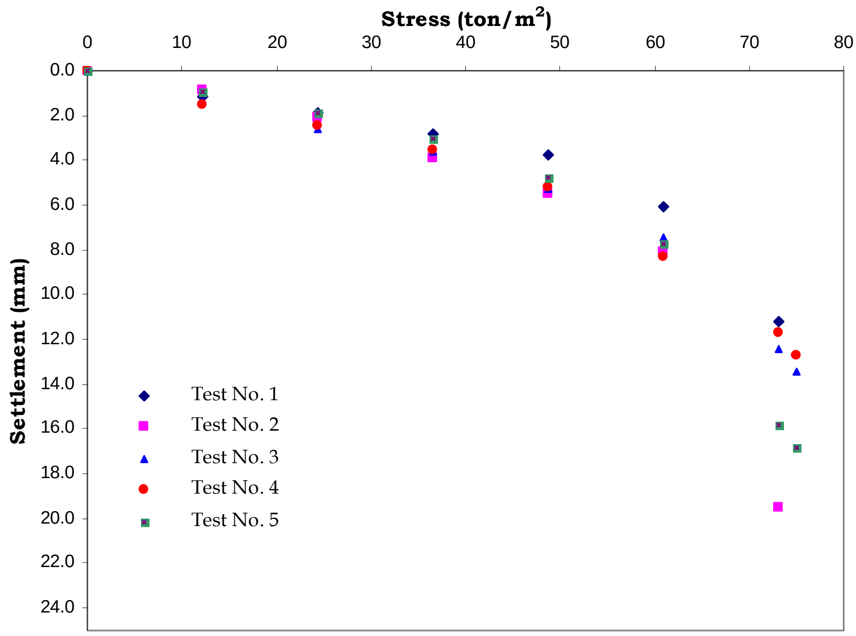

Figure (4.8): Stress versus settlement of 45 cm plate load test (Group 3)

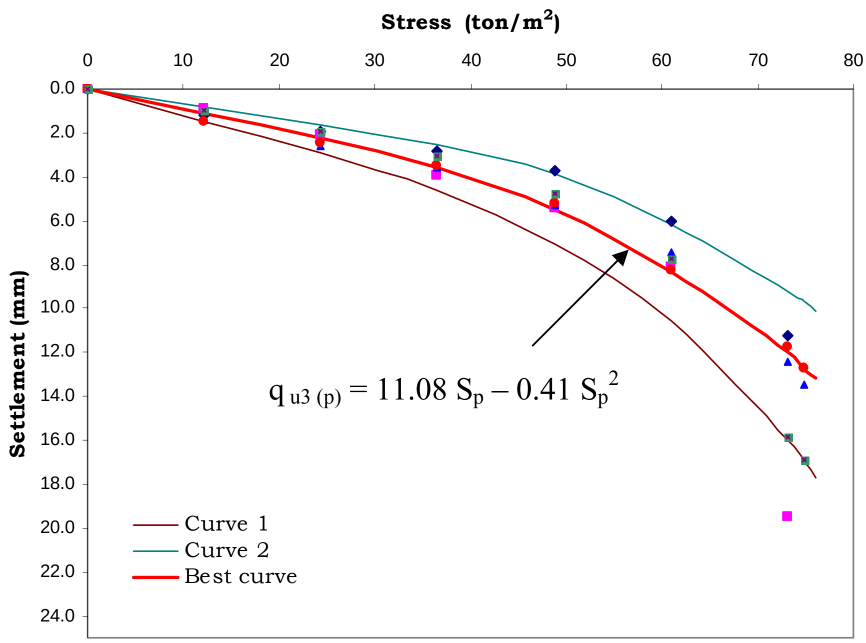

Figure (4.9): Best fitting curve to represent the average settlement values of 45 cm plate load test versus average stresses (Group 3)

Estimation of K for plate for each test

K_{plate} values were found out from performing plate load test experiment on sandy soil by figuring out the values of the plate settlement that compensate the settlement value of mat by using the equation of cohesionless soil as defined by the following metric unit equation by Das (1999) as follows:

$$S_{mat} = S_{platet}\left(\frac{B_F}{B_P}\right)^2\left(\frac{3.28B_P+1}{3.28B_F+1}\right)^2 \quad (4.6)$$

The researcher has worked out simple math to bring the Das equation (1999) in a very simple format as follows:

$$S_{mat} = S_{plate}\left(\frac{B_F(B_P+0.3)}{B_P(B_F+0.3)}\right)^2 \quad (4.7)$$

Where:

S_{mat}: mat settlement

S_{plate}: plate settlement

B_F: footing width

B_P: plate diameter

For 30 cm plate, B_P = 0.3 m, the settlement equation for cohesionless soil can be rewritten as follows:

$$S_{mat} = S_{P(30)}\left(\frac{B_F(0.3+0.3)}{0.3(B_F+0.3)}\right)^2 = S_{P(30)}\left(\frac{0.6B_F}{0.3(B_F+0.3)}\right)^2$$

As B_F (mat width) is larger than B_P (plate diameter), the above equation can be reduced and can be re written as follows:

$$S_{mat} \approx S_{P(30)}\left(\frac{0.6\mathrm{B_F}}{0.3\mathrm{B_F}}\right)^2 = S_{P(30)}(2)^2 \Rightarrow S_{mat} = 4S_{P(30)}$$

Likewise for 45 cm plate, B_P = 45 m, the settlement equation for cohesionless soil can be modified and re written as follows:

$$S_{mat} = S_{P(45)}\left(\frac{B(0.45+0.3)}{0.45(B+0.3)}\right)^2 = S_{P(45)}\left(\frac{0.75B}{0.45(B+0.3)}\right)^2$$

$$S_{mat} \approx S_{P(45)}\left(\frac{0.75B}{0.45B}\right)^2 = S_{P(45)}(1.67)^2 \Rightarrow S_{mat} = 2.8\,S_{P(45)}$$

In conclusion, it was found that for 30 cm plate diameter gives, $S_{mat} = 4\,S_{P(30)}$,while for 45 cm plate diameter, gives $S_{mat} = 2.8\,S_{P(45)}$

Table (4.4) contained the equivalent values of settlement in plate (S_{plate}) to settlement in mat (S_{mat}) using the concluded adaptation approximation equations.

Table (4.4): Equivalent values of settlement in plate S_{plate} to settlement in mat S_{mat}

S_{mat} (mm)	40	25	20	12	6
S_{30} cm plate Approximate (mm)	10	6.25	5	3	1.5
S_{45} cm plate Approximate (mm)	14.3	8.9	7.1	4.3	2.2

In group 1, knowing the values of plate settlement, the researcher easily located the pressure values using the best fitting curves established followed by finding the subgrade reactions by dividing the pressure over the settlement. Table (4.5) shows both pressure values against the settlement values and the subgrade reactions. Similarly the pressure values against the settlement values in addition to the subgrde reactions can be found in Table (4.6) and Table (4.7) for Group 2 and Group 3 respectively.

Table (4.5): Pressure values against the settlement values and the subgrade reactions K (Group 1)

S_{mat} (mm)	40	25	20	12	6
S_{30} plate (mm)	10	6.25	5	3	1.5
$q_{u\ (30)}$ t/m^2	46	34	29	18	8
K_{plate} t/m^3	4600	5440	5800	6000	5330

Table (4.6): Pressure values against the settlement values and the subgrade reactions K (Group 2)

S_{mat} (mm)	40	25	20	12	6
S_{45} plate (mm)	14.3	8.9	7.1	4.3	2.2
$q_{u\ (45)}$ t/m^2	83	64	55	39.5	24
K_{plate} t/m^3	5805	7190	7750	9190	10900

Table (4.7): Pressure values against the settlement values and the subgrade reactions K (Group 3)

S mat (mm)	40	25	20	12	6
S 45 plate (mm)	14.3	8.9	7.1	4.3	2.2
$q_{u(45)}$ t/m^2	78	62	56	41	23
K_{plate} t/m^3	5450	6950	7890	9500	10450

As discussed in section 4.4 a unified best fitting curve was established for each group. In group 1 the best fitting curve was derived for plate diameter of 30 cm while for the other two groups, the best fitting curves were created for plate load diameter of 45 cm. Therefore the researcher has compensated the stresses obtained when using plate diameter of 30 cm to the stresses of plate diameter of 45 cm based on Das (1999) for sandy soil as follows:

$$q_{u(F)} = q_{u(P)} \frac{B_F}{B_P} \qquad (4.8)$$

The researcher has set $q_{u(F)}$ and $q_{u(P)}$ to be as $q_{u(45)}$ and $q_{u(30)}$ respectively, the new form of the equation is as follows:

$$q_{u(45)} = q_{u(30)} \frac{B_{45}}{B_{30}} \qquad (4.9)$$

Where B_{45} = 0.45 m, and B_{30} =0.30 m

$$q_{u(45)} = q_{u(30)} \frac{0.45}{0.3} \Rightarrow q_{u(45)} = 1.5\ q_{u(30)}$$

Also, the settlement obtained from group 1 was modified to compensate the settlement of plate diameter of 45 cm based on the simplified equation of Das (1999) derived by the researcher as follows:

$$S_F = S_{Plate} \left(\frac{B_F\,(B_{30} + 0.3)}{B_{Plate}\,(B_{45} + 0.3)} \right)^2$$

The researcher has set the S_{mat} and S_{plate} to be as $S_{P(45)}$ and $S_{P(30)}$ respectively, the new form of the equation is as follows:

$$S_{P(45)} = S_{P(30)} \left(\frac{B_{45}\,(B_{30} + 0.3)}{B_{30}\,(B_{45} + 0.3)} \right)^2$$

$$S_{P45} = S_{P30}\left(\frac{0.45(0.3+0.3)}{0.3(0.45+0.3)}\right)^2 \Rightarrow S_{P45} = 1.2\ S_{P30}$$

By modifying both the stress and the corresponding settlement of group 1, the researcher produced a new curve to represent stress versus settlement for plate diameter 45 cm of group 1 adding together to the two best fitting curves of group 2 and 3 for plate diameter of 45 cm. Finally the researcher has developed a modified unified fitting curve from the best fitting curves of each individual group as clearly can be visualized in Figure (4.10).

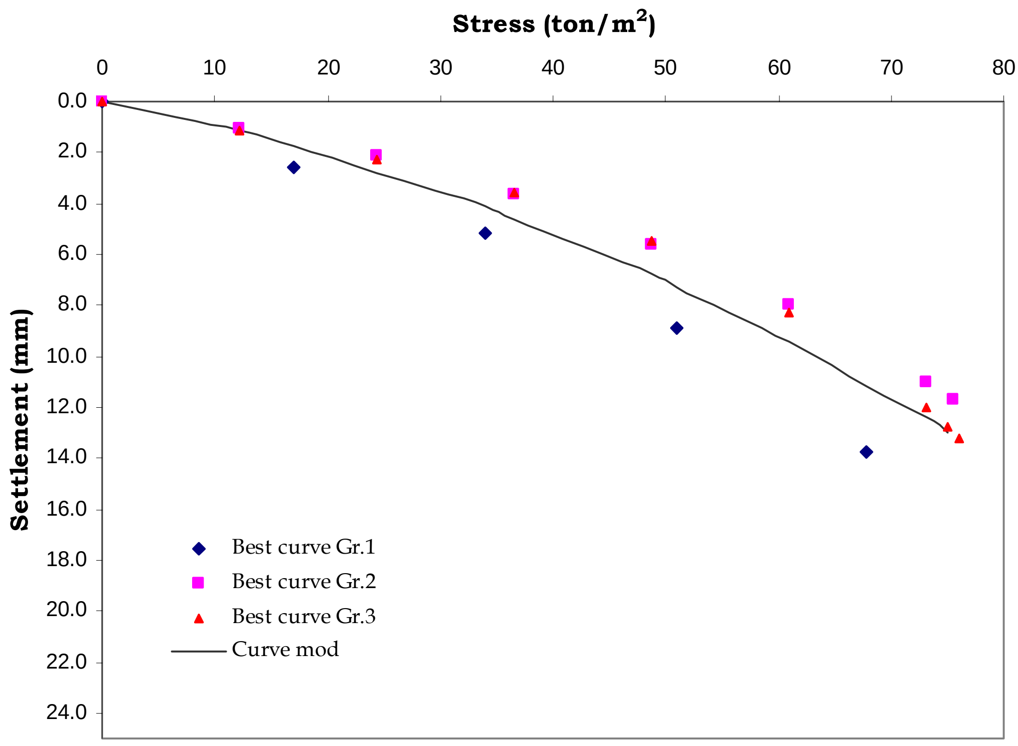

Figure (4.10): Modified unified curve obtained from the three best fitting curves to represent the average settlement values of 45 cm plate load test versus average stresses

From the modified unified best fitting curve of the three groups it can be seen that the relation between the stress versus the settlement can be represented as follows:

$$q_{u(P)} = 9.065\ S_p - 0.26\ S_p{}^2 \qquad (4.10)$$

Knowing that the correlation factor R^2 = 0.997 and the units of $q_{u(P)}$ and S_p are in t/m^2 and mm respectively. The coefficient of subgrade reaction of sand soil is represented as:

$$k_p = \frac{q_{u(P)}}{S_p\,(10)^{-3}} \qquad (4.11)$$

Replacing the value of $q_{u(P)}$ from equation (4.11) into the coefficient of subgrade reaction of sandy soil K_p gives the following equation:

$$k_P = \frac{9.065\ S_P - 0.26\ S_P{}^2}{S_p\ (10)^{-3}}$$

$$k_P = 9065 - 260\ S_P \qquad (4.12)$$

Where K unit is in t/m^3 and S_P unit in mm

The following Table (4.8) shows the values of stresses versus settlement of plate load test diameter of 45 cm using equation (4.11) or by using the modified unified best fitting curve of the three groups discussed in section 4.5 simultaneously with the values of K for plate using equation (4.12)

Table (4.8): Pressure values against the settlement values and the subgrade reactions K of the modified unified best fitting curve

S_{mat} (mm)	40	25	20	12	6
S_{45} plate (mm)	14.3	8.9	7.1	4.3	2.2
$q_{u(45)}$ t/m^2	76.5	60	51	34	18.7
K_{plate} t/m^3	5350	6740	7180	7910	8500

By knowing the K_{plate} and S_p , the values of K_{mat} and S_{mat} can be found using $k_{mat} = 0.25\ k_{Plate}$ and $S_{mat} = 2.8\ S_P$ respectively. Therefore by applying simple math, the researcher came up with the following simplified equation::

$$k_{mat} = 0.25\ (9065 - 260\ S_P) = 0.25\left(9065 - 260\left(\frac{S_{mat}}{2.8}\right)\right)$$

$$k_{mat} = 2266 - 23\,S_{mat} \qquad (4.13)$$

As it can be seen at settlement 25 mm of a footing, the value of K for mat can be taken as:

$k_{mat} = 2266 - 23(25) = 1690\,t/m^3$

The values of coefficient of subgrade reaction of mat foundation on sandy soil K for mat using the equation (4.3) is summarized in Table (4.9).

Table (4.9): Values of coefficient of subgrade reaction of mat foundation on sandy soil K_{mat} using the equation (4.3)

S_{mat} (mm)	40	25	20	12	6
k_{mat} t/m^3	1345	1690	1800	1990	2130

Bowels equations

As it was explained earlier in the thesis that Bowels (1997) had reported a relation between allowable bearing capacity of soil and the coefficient of subgrade reaction as $K_{footing}$= 40 F.S q_{all} knowing that this relation was formed based on a settlement of 25 mm but this value of K is for mat or footing and in this case an alteration is needed to convert K for mat to a K for a plate and by looking at equation (2.15) knowing that the b value (Plate diameter) is very small compared to the value of B (mat width), it can be concluded that K for mat is approximately equal one quarter of K plate ($K_{footing}$ = 0.25 K_{plate}) and as a result the equation can be re written as follows:

K_{plate} = 4 (40) F.S q_{all} = 160 FS q_{all} and by setting the factor of safety to be 4 and the q_{all} = 15 ton/m^2 (from Islamic University soil and material laboratory), this will adjust the value of K plate as follows:

K_{plate} = 160 (4) (15) = 9600 ton/m^3

The above calculations was pursued based on settlement of 25 mm. correspondingly, the value of K for the plate of settlement 20 mm is as follows:

K_{plate} = 200 F.S q_{all} = 12000 ton/m^3, the following Table (4.10) includes the values of K plate at different settlements

Table (4.10): K_{plate} values at different settlements based on Bowel formula (1997)

Settlement (mm)	40	25	20	12	6
$K_{Footing}$ t/m^3	1,500	2,400	3,000	5,000	10,000
K_{Plate} t/m^3	6,000	9,600	12,000	20,000	40,000

It can be noticed that by considering small settlement of 6 mm using Bowel formula (1997) it gives a large value of 40,000 ton/m^3 for K and this was surprisingly very high as the maximum value of K in preceding tables (4.5), (4.6) and (4.7) was 10,900 ton/m^3 which represent a quarter of the numerical value obtained by Bowels (1997); therefore it is clear evidence that Bowels formula (1997) supply large values of K in case of small settlement and this likely because the pressure under small settlement is way less than the value of the ultimate bearing capacity. However when considering large settlement it gives reasonable close values because the value of the ultimate bearing capacity is close to the pressure value around the large settlement.

Chapter 5

Finite Element Analysis and Results

5.1 Introduction

A finite element model analysis of mat is based on the theory of flat plate bending being supported by the soil which is modeled as a dense liquid using Winkler Springs. Commercial softwares based finite element programs are readily available today and are capable of easing the engineer's workload, yet will provide a sophisticated solution to a complex problem. The finite element method can also consider important effects ignored by some of the other mat analysis methods, the most important effect being "dishing action" of the mat foundation on the compressible substratum.

The finite element method is a numerical method for solving problems of engineering and mathematical physics and in this method the mat is idealized as a mesh of discrete elements interconnected at the nodal points. The soil is modeled as a series of Winkler Springs which are located at each node in the computer model. Normally, three degrees of freedom exist at each node, a vertical deflection and a rotation about each of the in plane axes as shown in Figure (5.1). External loads may be applied in these same directions. The internal stress resultants (two orthogonal in-plane moment vectors and, for some elements, a vertical shear) are related to the degrees of freedom of the element by a stress matrix derived from the finite element displacement function.

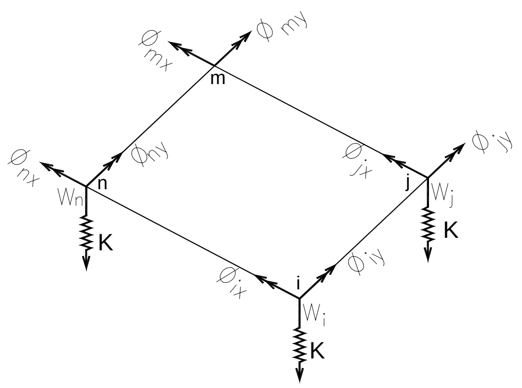

Figure (5.1): Rectangular plate element with nodal degrees of freedom

5.2 Analysis Assumptions

There are several assumptions must be made in using the finite element approach:

1- Commonly, it is assumed that the mat acts as an isotropic, homogeneous, elastic solid in equilibrium.

2- The subgrade reactions are vertical vectors and are proportional to the deflection of the node. The springs are such that only compression is resisted. All nodes must be reviewed for tensile support reactions. The spring constant at supports resisting tension must be set to zero, and a new analysis performed. This iterative procedure must be repeated until no tension resistance at the mat-soil interface occurs.

3. The subgrade reaction is equal to the spring constant at a node multiplied by the deflection of that node.

Prior to any computerized analysis, assumptions must be made regarding mat size and thickness. It is important that initial mat dimensions be carefully selected to avoid costly remodeling of the mat foundation with each geometry change. The finite element analysis is then used not only to verify mat sizing but also to determine the soil pressure distribution, mat displacements, and internal finite element stresses and forces.

5.3 Mat Dimension Selection

The selection of mat plan dimensions is primarily based on limiting the mat contact pressure to within the limits prescribed by the soil consultant. Mats must be sized such that the gross bearing pressure under the mat allows for an adequate margin of safety with respect to soil failure. Also, serviceability considerations dictate that the magnitude of the uniform and differential mat settlement must be limited. The mat dimensions will be used for analysis in this chapter is similar to that of mat dimensions stated in chapter 2 as shown in Figure (2.7).

5.4 Mat Thickness Selection

The mat thickness is primarily proportioned based on punching shear provisions of ACI-318-05 at the typical column locations. The mat thickness has been selected such that no shear reinforcement at the typical mat section that requires relatively low concrete strengths.

5.5 Finite Element Type Selection

There are many different types of elements available for performing a finite element mat analysis and some of the different available types that are in use by practitioners of mat analysis will follow in subsequent sections within chapter 5.

5.5.1 Flat Plate Elements Neglecting Transverse Shear Deformation

Flat Plate Elements Neglecting Transverse Shear Deformation are used when the plate thickness is much smaller than its in-plane dimensions (length and width), then transverse shear deformation should not be used. These elements are commonly used for finite element mat analysis. They are the most economical, are simple to use, and yield reasonable displacement and moment values. Most of the available solutions using elements of this type do not yield transverse shear values. These elements are usually stiffer than the actual mat element. This implies non-conservative displacements and, most commonly, conservative moments emanating from the analysis.

5.5.2 Flat Plate Elements with Transverse Shear Deformation (Thick plate)

Flat Plate Elements with Transverse Shear Deformation are used when the plate thickness is more than about one tenth the span of the plate, then the transverse shear deformation must be accounted for and the plate is then said to be thick. These elements are isoparametric elements. Solutions result in conforming elements that usually yield good results. Use of these elements results in solutions that are less predictable than those using conventional elements because they are more sensitive to the mat geometry, they can result in ill-conditioned stiffness equations and can yield diverging results. They are sensitive to the mat thickness and should not be used on thin mats. These elements are more flexible than the actual mat element, hence they can result in solutions that yield displacements and moments with higher accuracy.

5.5.3 Solid Element

Solid element is a three dimensional solid and is a very expensive and laborious element to use. They have the advantages that of considering transverse strain.

5.6 Finite Element Mesh Generation

This paragraph will tutor the reader to create a good finite element mesh based on the minimum number of finite elements used in the analysis and will help to understand both the mat geometry and loading conditions of the potential established finite element model. A nodal point existed at all column locations, concentrated loads, and along the boundaries of an area that has a distributed loading of different magnitude than the rest of the mat. The major grid lines were used to discretize the mat and determined by drawing intersecting lines through the column joints, concentrated load locations, and along the boundaries of the distributed loading area, as illustrated in Figure (5.2) and Figure (5.3).

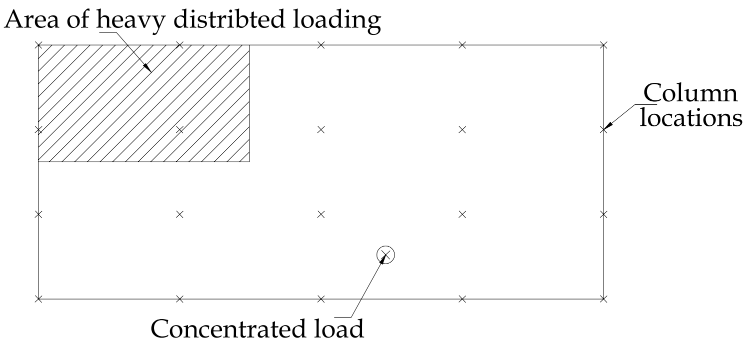

Figure (5.2): Mat geometry and loading

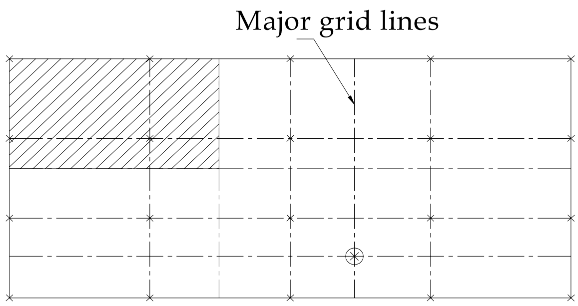

Figure (5.3): Discretizing mat with the major grid lines

It is common in many mat systems for a column joint location to be slightly offset from a grid line containing several column joints. In an effort to simplify a mat model, Daryl Logan (2002) has shown that the results of the analysis are not affected appreciably whenever a lightly loaded column is "shifted" slightly from the offset position to the common grid line. The researcher has assessed each occurrence to determine whether the analysis will be affected by this practice. The major grid lines produced the minimum number of finite elements for the particular mat geometry.

The researcher addressed the level of accuracy that is desired from the analysis as well as cost considerations and determined whether his mesh be refined to produce smaller finite elements. The mesh has refined by supplementing the model with minor grid lines between the major grid lines. An "ideal" mat model would have a fine mesh near the column concentrated load locations and a coarser mesh at some distance from the concentrated loads. It is not necessary to arbitrarily use this ideal gradating mesh throughout the entire mat. This refinement has been found necessary only at some locations. Factors helped to determine the degree of refinement are considered the relative magnitude of the column loads, column spacing, and the relative positions of the loads within the mat. The final mesh consisted of finite elements with an aspect ratio, length/width, near unity and has interior angles less than 180° and long slender elements and elements with sharp angles were avoided.

5.7 Soil Structure Interaction – Determination of Spring Modulus

The interaction of the compressible soil material with the mat foundation is modeled with finite elastic springs connected to the nodal points in the model. The behavior of the soil material is represented by a modulus of subgrade reaction value. The modulus of subgrade reaction varies throughout the domain of the mat area and it is taken for simplicity to be a constant value throughout. The use of a varying or uniform modulus of subgrade reaction is dependent upon the type of soil material, general behavior of the mat subjected to the applied loading, type of applied loading, and the degree of accuracy refinement required for the design of the mat system. The modulus of subgrade reaction is used to compute node springs based on the contributing plan area of an element to any node. The required calculation for determination the magnitude of the finite elastic spring constants is illustrated in Figure (5.4).

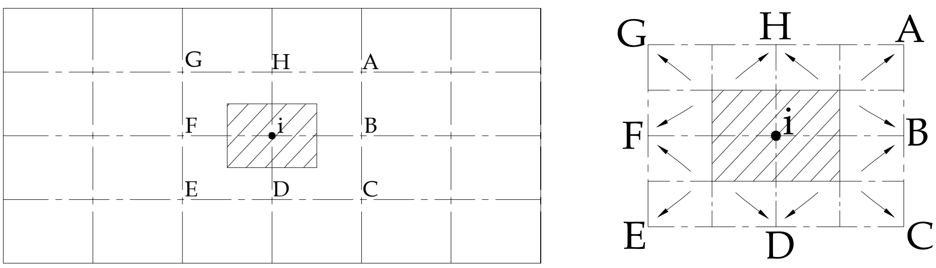

Figure (5.4): Mat discretization

K_i = Spring constant at node i (t/m)

k_s = Modulus of subgrade reaction (t/m^3)

A_i = tributary area contribution of finite element to node i (m^2)

$$A_i = \frac{1}{4}(A_{ABIH}) + \frac{1}{4}(A_{BCDI}) + \frac{1}{4}(A_{DEFI}) + \frac{1}{4}(A_{FGHI})$$

$$K_i = k_s, (t/m^3)\, x\, A_i, (m^2) = units\ of\ t/m$$

These calculations are laborious for hand calculations; however, it is a rather than trivial task to develop a computer program for preprocessing the information to obtain the spring constant values. The following section will discuss the use of two available commercial software SAP2000 version 11 and SAFE version 8 to construct a finite element model to be used for analysis of the mat foundation as described in Figure (2.7).

5.8 SAP 2000 Software

The geometry and the dimensions of mat foundation as well as the applied loads on centers of columns revealed in Figure (2.7) of chapter 2 were entered to construct the finite element model using the latest version of sap 2000. The obtained experimental numerical value of subgrade reaction was taken from chapter 4 and it was found to be 1500 t/m^3. The mat thickness was considered to be 80 cm based on punching shear computations. The loads applied to the column has not been entered as a concentrated point load on center of the column to avoid receiving sharp value of the moment under the center of the column as this will be in deed not a real representation for the moment as shown in Figure (5.5).

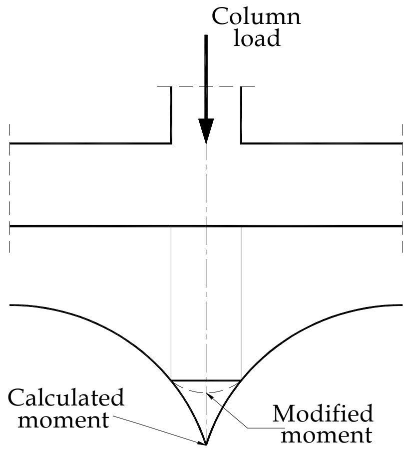

Figure (5.5): Moment shape due to a point concentrate load

The researcher has chosen another way to enter the applied loads on columns by entering that applied loads on columns as an equivalent pressure through dividing the applied column point load by the calculated area that fallout where the applied point column load reach half of mat thickness (t=45 cm) of a given slope of 1:1 downward of mat as shown in Figure (5.6). The subjected pressure numerical values applied on the computed areas are shown in Figure (5.8) and Table (5.1).

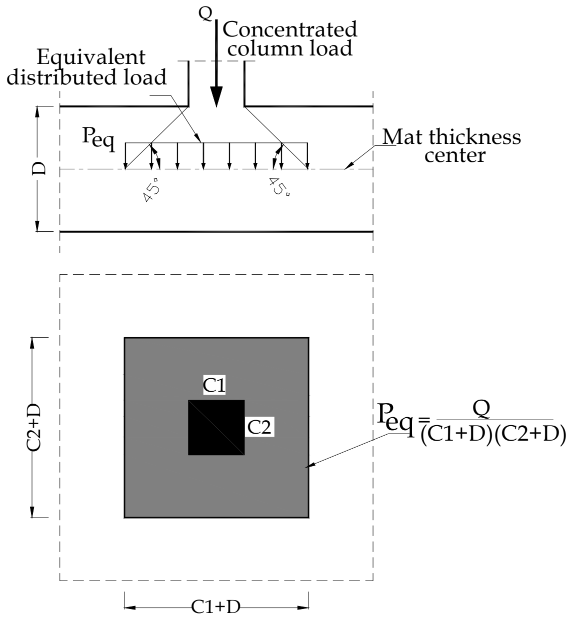

Figure (5.6): Load transfer mechanism indoor the mat thickness

The mat was meshed by dividing it into a number of elements; the size of the element was measures to be 0.25m by 0.35m, the layout of the mesh of mat finite element model can be seen in Figure (5.7).

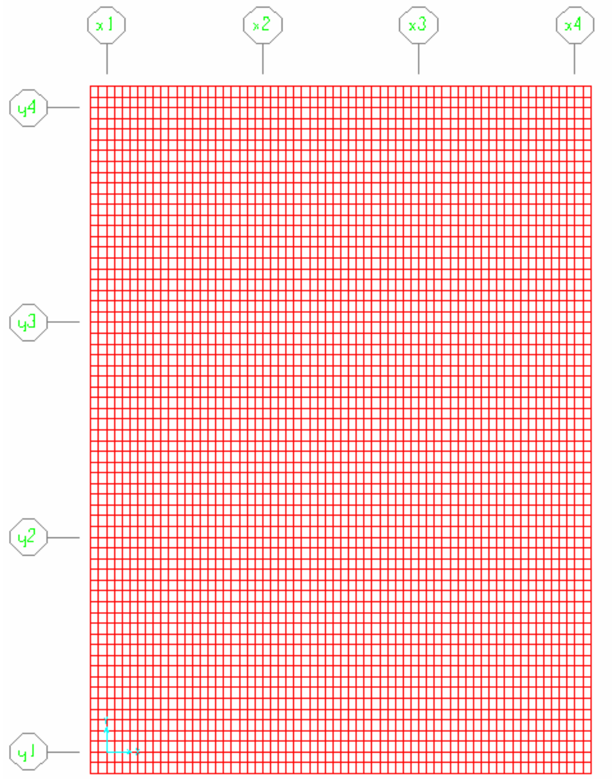

Figure (5.7): Mat mesh layout using Sap 2000

The joint spring for the interior node, the corner nodes and the edge nodes were estimated as follows:

- Interior nodes $K_i = k_s$ x A_i =1500 (0.25*0.35) = 131.25 t/m
- Corner nodes $K_c = k_s$ x A_c =1500 [0.25*(0.25*0.35)] = 32.81 t/m
- Edge nodes $K_e = k_s$ x A_e =1500 [0.5*(0.25*0.35)] = 65.63 t/m

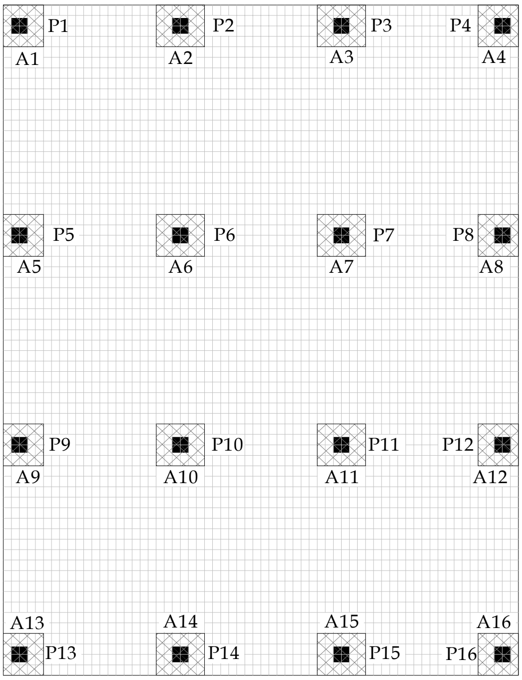

Figure (5.8): Applied pressures on the computed columns surrounded areas

Table (5.1): Applied pressure and computed areas

Pressure designation	Dead Load (t/m^2)	Live Load (t/m^2)	Area No.	Area (m^2)
P1	44.57	22.29	A1	1.75
P2	76.24	38.12	A2	2.10
P3	68.86	34.43	A3	2.10
P4	38.34	19.17	A4	1.75
P5	89.83	44.91	A5	1.75
P6	153.86	76.93	A6	2.10
P7	140.62	70.31	A7	2.10
P8	79.03	39.51	A8	1.75
P9	76.46	38.23	A9	1.75
P10	133.52	66.76	A10	2.10
P11	136.57	68.29	A11	2.10
P12	77.71	38.86	A12	1.75
P13	34.46	17.23	A13	1.75
P14	60.71	30.36	A14	2.10
P15	62.67	31.33	A15	2.10
P16	35.77	17.89	A16	1.75

The shear force and mat moment distribution in Y-direction are shown in Figure (5.9) and Figure (5.10) respectively.

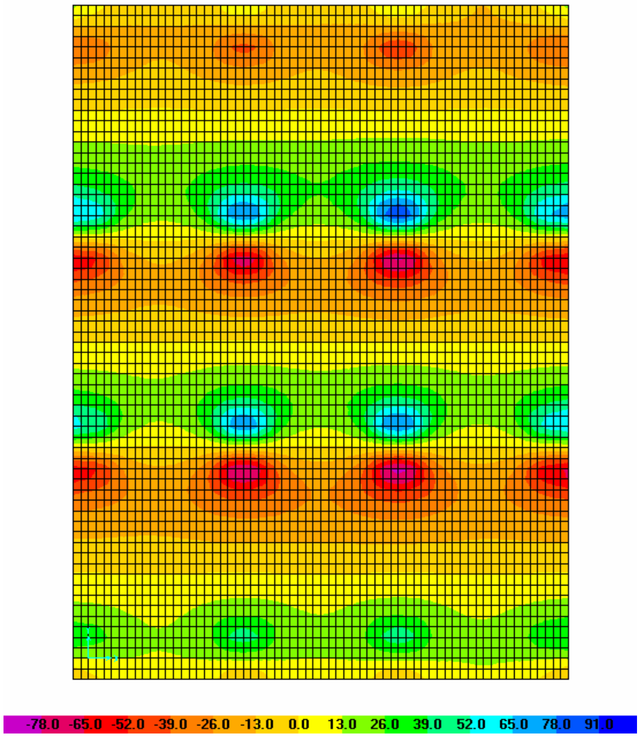

Figure (5.9): Shear force of mat in y-direction

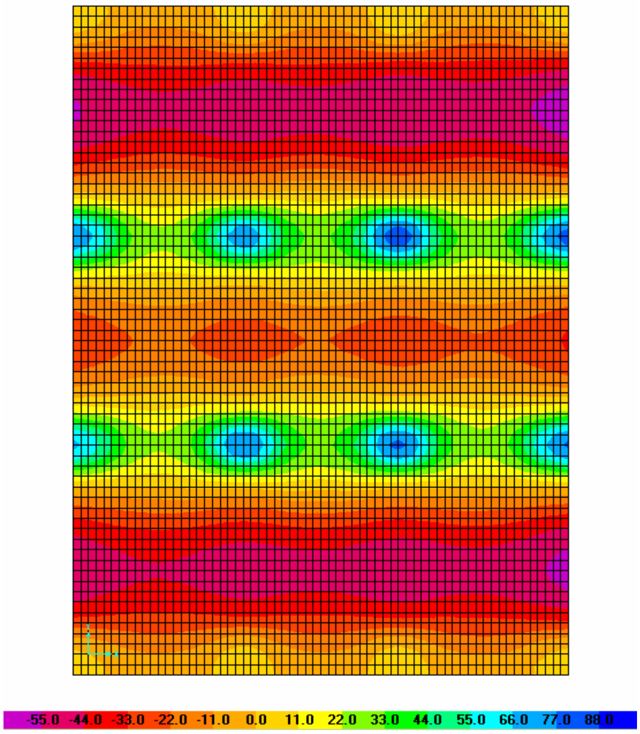

Figure (5.10): Moment distribution of mat in y-direction

In Sap 2000 it is difficult to display graphically the numerical values of shear force and bending moment for each individual strip of mat finite element model, the researcher however obtained the numerical values for each strip from the output database file and drew the shear force and bending moment diagrams. The shear force and the bending moment diagrams for the four different strips using SAP2000 program can be found from Figure (5.11) to Figure (5.18).

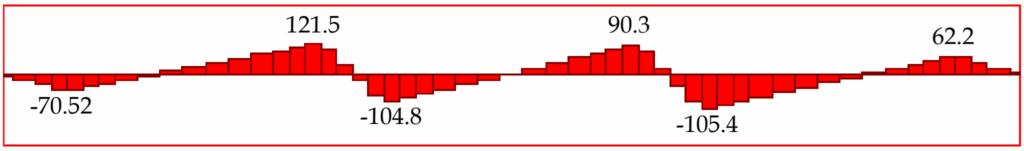

Figure (5.11): Shear force diagram for strip ABMN using SAP2000 program

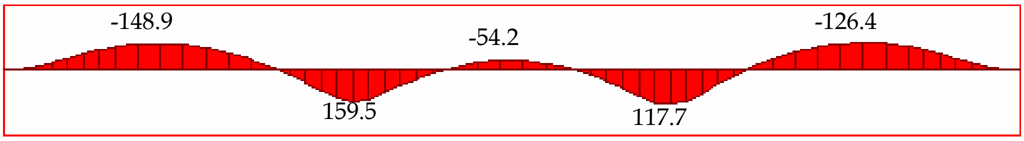

Figure (5.12): Bending moment diagram for strip ABMN using SAP2000 program

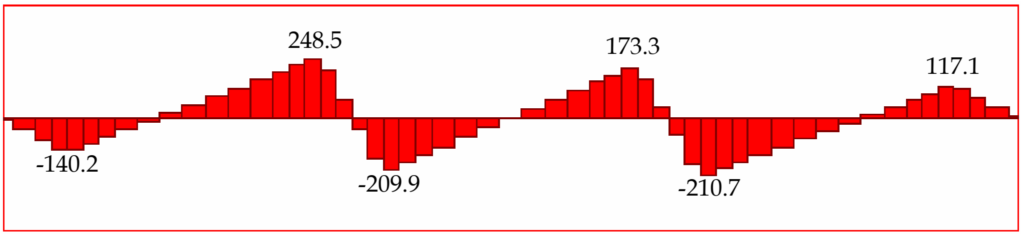

Figure (5.13): Shear force diagram for strip BDKM using SAP2000 program

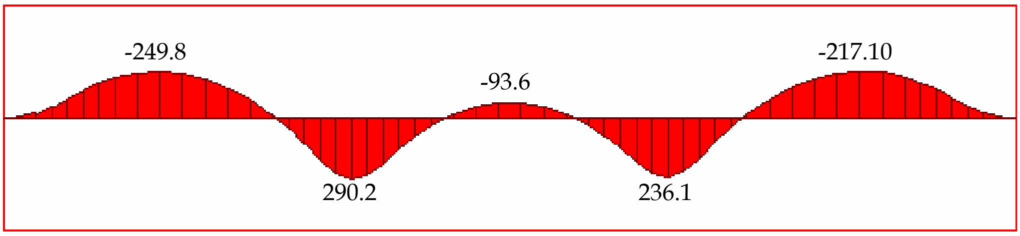

Figure (5.14): Bending moment diagram for strip BDKM using SAP2000 program

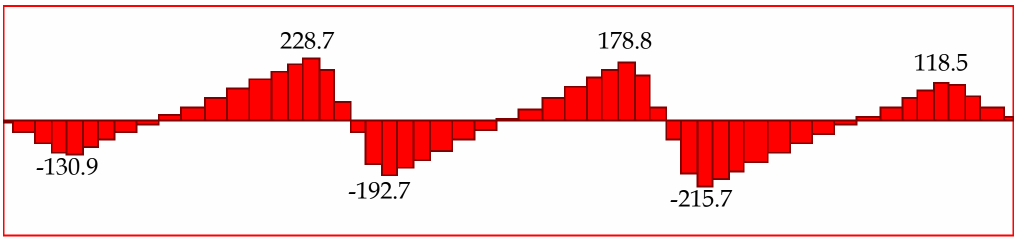

Figure (5.15): Shear force diagram for strip DFIK using SAP2000 program

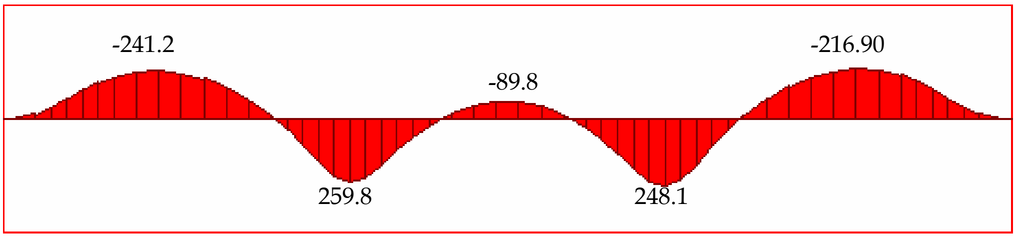

Figure (5.16): Bending moment diagram for strip DFIK using SAP2000 program

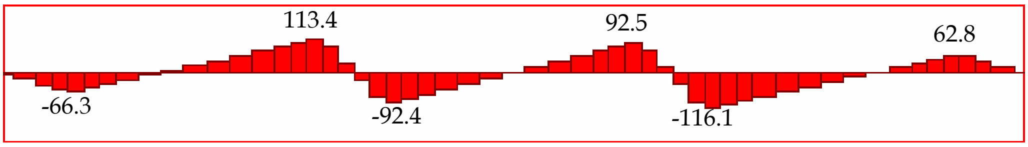

Figure (5.17): Shear force diagram for strip FGHI using SAP2000 program

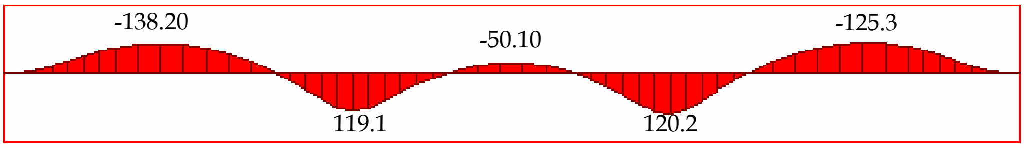

Figure (5.18): Bending moment diagram for strip FGHI using SAP2000 program

5.9 SAFE Software Overview

SAFE is a sophisticated, yet easy to use, special purpose analysis and design program developed specifically for concrete Slab/Beam, Basement/Foundation systems. SAFE couples powerful object-based modeling tools with an intuitive graphical interface, allowing the user to quickly and efficiently model slabs of regular or arbitrary geometry with openings, drop panels, ribs, edge beams, and slip joints supported by columns, walls or soil.

The analysis is based upon the finite element method in a theoretically consistent fashion that properly accounts for the effects of twisting moments. Meshing is automated based upon user specified parameters. Foundations are modeled as plates or thick plates on elastic foundations, where the compression only soil springs are automatically discretized based upon a modulus of subgrade reaction that is specified for each foundation object.

5.9.1 SAFE Software Finite Element Analysis

The mat dimensions was entered in SAFE program and was automatically meshed based upon the maximum mesh dimension, in this model the researcher used an element dimension 0.5 m by 0.5 m. The mesh layout for the mat foundation, the redistribution of column loads and the computed areas surround the columns are shown in Figure (5.19) and Table (5.2). The Subgrade modulus for soil under the mat was 1500 t/m^3 as mentioned in chapter 4. The out put of both shear force and moment diagrams on mat received from the analysis are represented in Figure (5.20) and Figure (5.21). It was noticed that unlike the structural analysis program SAP 2000, the structural analysis software SAFE allows the user to draw the shape of the shear and bending moment diagrams separately for each individual strip, Figures from (5.22) to Figures (5.25) respectively represent the shear and bending moment diagrams for the mat.

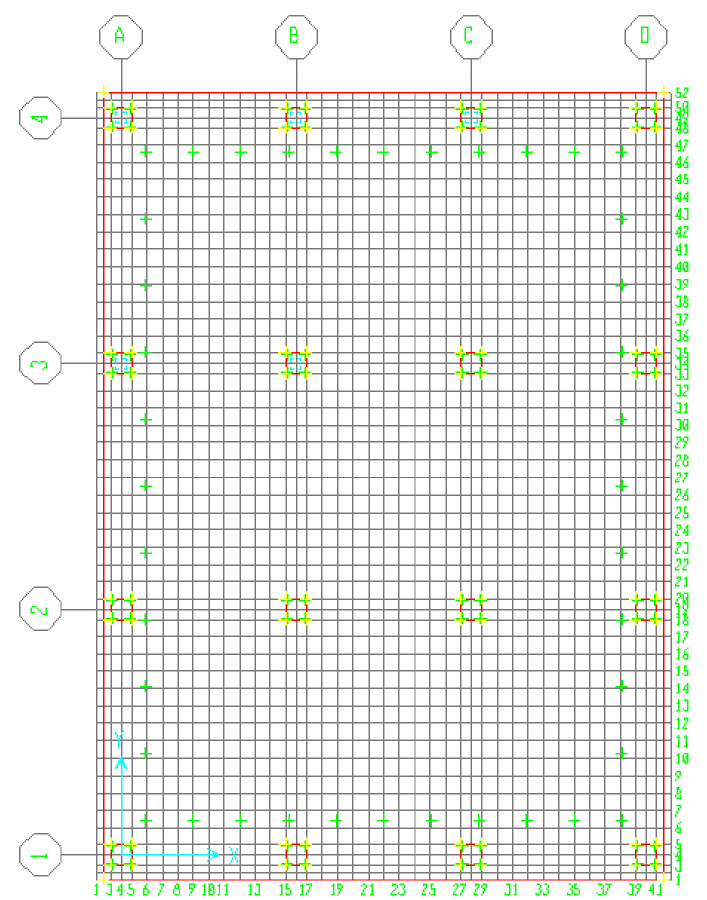

Figure (5.19): Mat mesh layout using SAFE

Table (5.2): Applied pressure on corresponding computed areas as a result of load transfer mechanism.

Pressure designation	Dead Load (t/m^2)	Live Load (t/m^2)	Column Area (m^2)
P1	216.67	108.33	0.36
P2	444.72	222.36	0.36
P3	401.67	200.83	0.36
P4	186.39	93.19	0.36
P5	436.67	218.33	0.36
P6	897.50	448.75	0.36
P7	820.28	410.14	0.36
P8	384.17	192.08	0.36
P9	371.67	185.83	0.36
P10	778.89	389.44	0.36
P11	796.67	398.33	0.36
P12	377.78	188.89	0.36
P13	167.50	83.75	0.36
P14	354.17	177.08	0.36
P15	365.56	182.78	0.36
P16	173.89	86.94	0.36

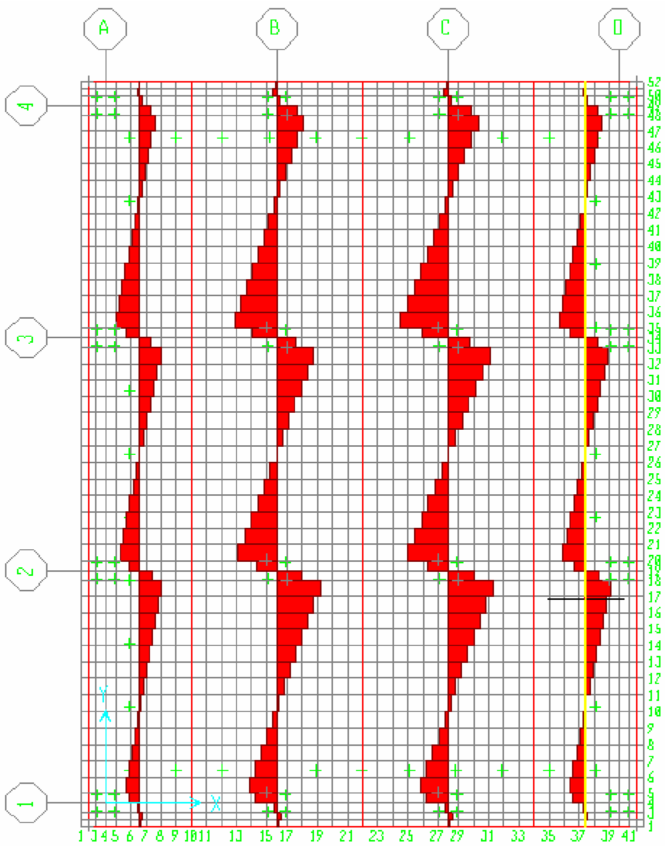

Figure (5.20): Shear force diagram drawn on mat in y-direction

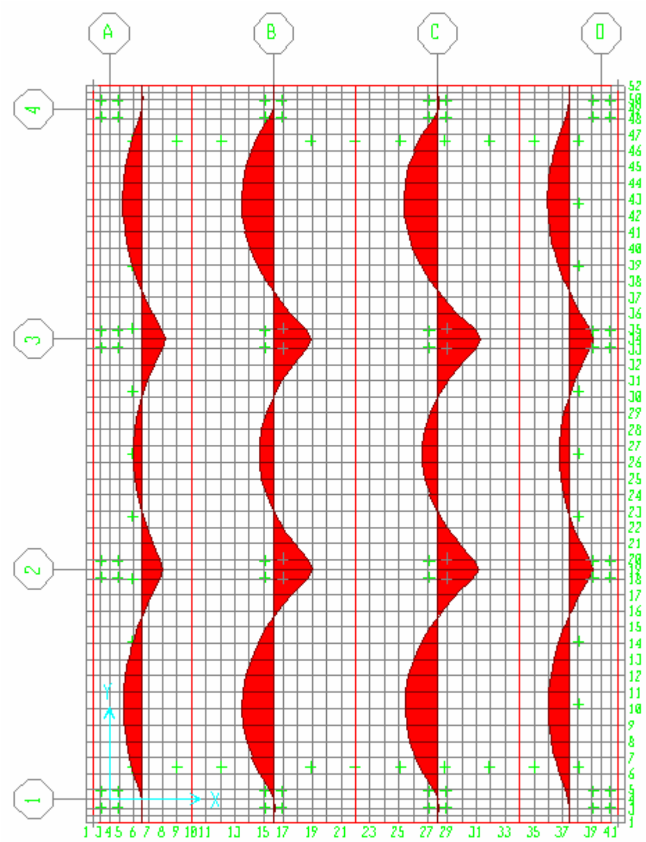

Figure (5.21): Bending moment diagram drawn on mat in y-direction

Figures (5.22) to (5.29) respectively represents the shear force and the bending moment diagrams for strips ABMN strip, BDKM strip, DFIK strip, and FGHI strip using SAFE program.

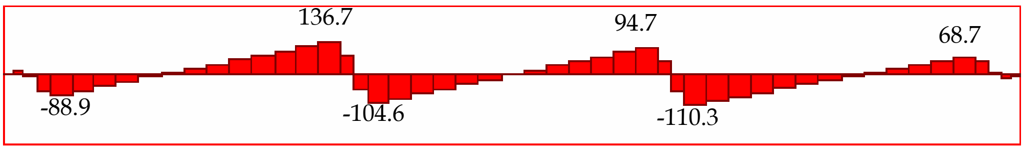

Figure (5.22): Shear force diagram for strip ABMN using SAFE program

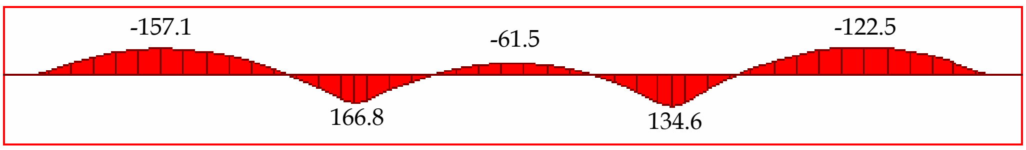

Figure (5.23): Bending moment diagram for strip ABMN using SAFE program

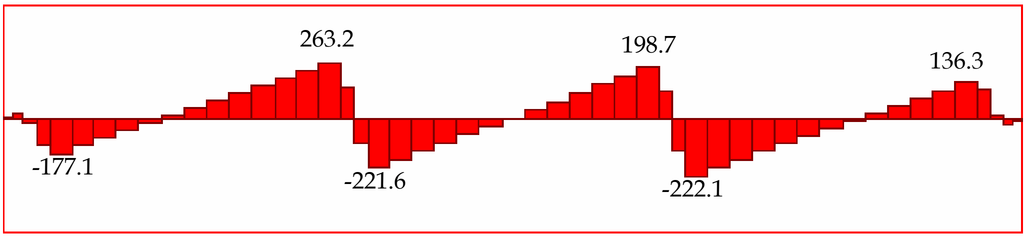

Figure (5.24): Shear force diagram for strip BDKM using SAFE program

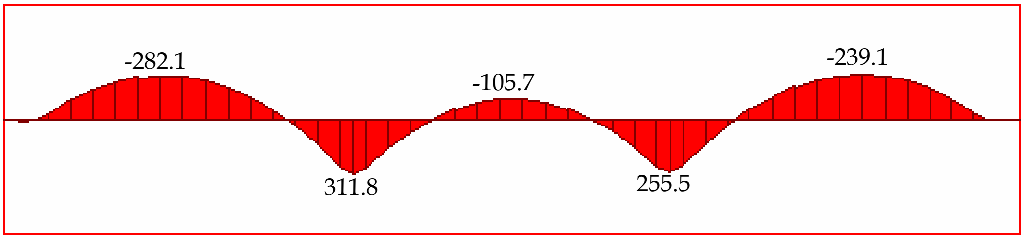

Figure (5.25): Bending moment diagram for strip BDKM using SAFE program

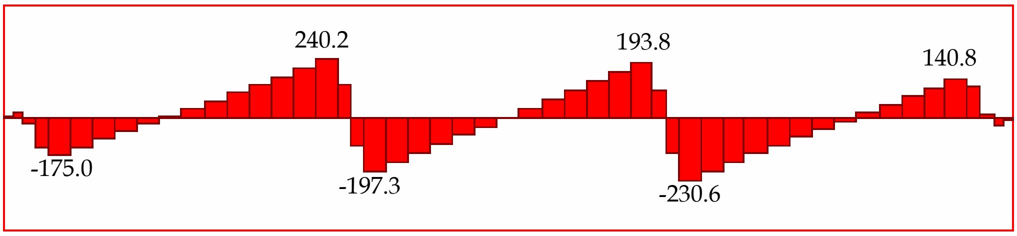

Figure (5.26): Shear force diagram for strip DFIK using SAFE program

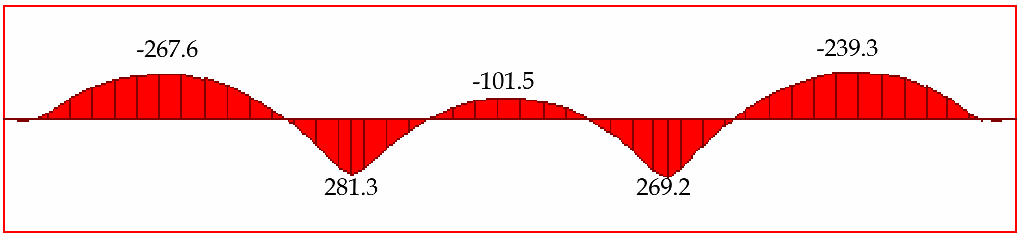

Figure (5.27): Bending moment diagram for strip DFIK using SAFE program

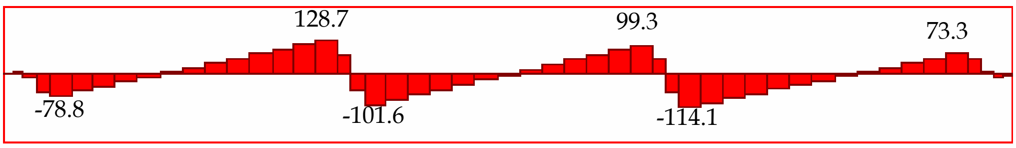

Figure (5.28): Shear force diagram for strip FGHI using SAFE program

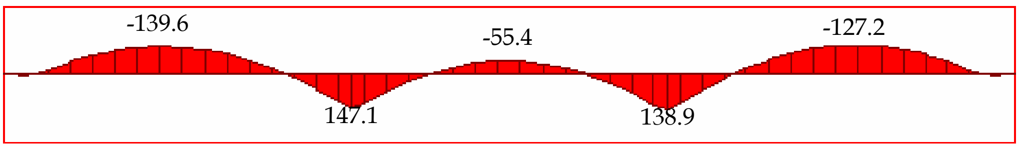

Figure (5.29): Bending moment diagram for strip FGHI using SAFE program

Chapter 6

Discussion of Results

6.1 Discussions

Previous chapters of the thesis discussed number of ways for the analysis of mat foundation placed on sandy soil located in a location to the west of Dair-Albalah area in Gaza strip as can be seen in Figure (2.7). The analysis was performed first using the conventional rigid method, this method based on two sets of modification factors for column loads and for soil pressures at both ends of each of the individual strips to satisfy the equilibrium equation on vertical forces to construct shear force diagrams but this way of analysis however is not true when a designer engineer attempt to construct a bending moment diagram as the equilibrium equation is not satisfied because the summation of moments around end point does not go to zero and as a consequence establishing accurate bending moment graph is a real test as it was clarified in chapter 2. The second way of mat analysis was suggested by the researcher of this thesis called the modified conventional rigid method and it contains three suggestions to overcome the problem when constructing the bending moment as described in fine points in chapter 3. The third method of mat analysis was employing finite element method using two available latest versions of structural analysis programs SAFE and Sap 2000 as demonstrated in chapter 5. Table (6.1) summarized the obtained numerical values of the bending moment of strip B D K M received from the analysis using the conventional rigid method. The suggested modified method by the researcher of the manuscript and the finite element method using the latest version of both Sap 2000 and SAFE. From Table (6.1) it was noticed that the obtained numerical moment values of the strip BDKM of mat foundation analysis using the conventional rigid method are considered divergent, for instance it was found that the numerical value of the moment (301.69 ton-m) at the end of the strip represents the product of the average load by the distance lies between the line of action of the modified columns resultant force and the line of action of the resultant force of the modified pressure under the strip. In chapter 3 it was shown that there are three suggestions by the researcher to modify the conventional method and was found the third suggestion of the modified conventional rigid method is the best one among the three and still lies between the first two suggestions as discussed earlier in previous chapters and by looking at Table (6.1), it is evident that the numerical values of the bending moment obtained by the modified conventional rigid method suggested by the researcher are less than that of conventional rigid method and larger than that of the finite element analysis approach of analyzing the mat foundation using two structural analysis programs of Sap 2000 and SAFE for that reason it was a clear proof by looking at the moment values obtained by SAFE structural analysis softwares finite element models based presented in Table (6.1) that the engineer can reduce the numerical value of the bending moment of the modified rigid method up to 15 percent and up to 20 percent when moment values compared the moment numbers obtained from structural analysis Sap 2000 program. It is beneficial to know that the moment values obtained from the running established finite element mat models using sap 2000 and SAFE programs give lesser moment values and it looks reasonable and this is because the soil pressure under the mat was analyzed in two direction not in only one direction like the conventional rigid and the modified rigid method suggested by the writer of thesis.

Table (6.1): Bending moment values of strip B D K M using different methods of mat analysis

Solution	Exterior Span (t.m)		Interior Span (t.m)		Exterior Span (t.m)		
	Exterior + ve	Interior -ve	Interior + ve	Interior -ve	Interior + ve	Interior -ve	Exterior + ve
Conventional Rigid	20.52	-352.03	287.5	-292.46	72.96	-561.00	284.85
Modified Conventional Rigid	20.95	-328.48	359.12	-135.37	304.75	-281.34	16.41
Finite Element using Sap2000	-	-249.8	290.2	-93.6	236.1	-217.1	-
Finite Element using SAFE	-	-282.1	311.8	-105.7	255.5	-239.1	-

Considering the values of the shear force obtained from the conventional rigid, it can be visualized that the shear force diagram was drawn exactly at the center of the support as it is assumed that the load is concentrated there but for the values of shear force obtained by finite element analysis was taken from the face of the support at distance of half of the depth and this what considered when doing the comparisons with the other method as can be seen in Table (6.2). This table summarized the results obtained by the conventional rigid method, modified conventional method proposed by the researcher and the finite element analysis.

Table (6.2): Numerical values of shear force for strip B D K M using different methods of mat analysis[1]

Column No.	Q_2		Q_6		Q_{10}		Q_{14}	
Solution	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
Conventional Rigid	-	-223.29	295.41	-276.75	211.31	-281.85	175.50	-
Modified Conventional	-	-217.20	308.71	-254.36	233.69	-268.84	180.78	-
Finite Element using Sap2000	-	-140.2	248.5	-209.9	173.3	-210.7	117.1	-
Finite Element using SAFE	-	-177.1	263.2	-221.6	198.7	-222.1	136.1	-

From Table (6.2) it can be noticed that the values of the shear force obtained used the conventional rigid method and the modified rigid method proposed by the researcher are very close and greater than those obtained by finite element using SAFE of about 13 percent and a bit more than 16 percent of those obtained by finite element using Sap 2000. The suggested reduction of bending moment and shear force values for the modified rigid method suggested by the researcher are applied to the other strips, for the other strips considered in the mat analysis please refer to Appendix A.

Based on a careful comprehensive analysis for a number of reports of old plate load tests experiments done by material and soil laboratory of Islamic University of Gaza on sandy soil along with the plate load tests on sandy soil performed by the researcher, a best unified fitting curve for the best fitting curves of each individual group as discussed in chapter 4 was successfully developed to help the researcher to create a simplified relation to calculate the coefficient of subgrade reactions K of sandy soil as a function of known settlement $K_{mat} = 2266 - 23\ (S_{mat})$ and this relation was compared to the Bowels relation (1997). It was observed that by considering small settlement of 6 mm using Bowel formula (1997) it gives a large value of 40,000 ton/m^3 for K and this was surprisingly very high as the maximum value of K in preceding tables (4.5), (4.6) and (4.7) was 10,900 ton/m^3 which represent a quarter of the numerical value obtained by Bowels (1997); therefore it is clear evidence that Bowels formula (1997) supplies large values of K in case of small settlement and this likely is because the pressure under small settlement is way less than the value of the ultimate bearing capacity however when considering large settlement it gives reasonable close values because the value of the ultimate bearing capacity is close up to the pressure value around the large settlement.

Chapter 7

Conclusions and Recommendations

7.1 Summary

A hand detailed example relating to the analysis of mat foundation using the conventional rigid method was included in the thesis to better understand the problems associated with this method was reviewed in chapter 2, it is anticipated that the information provided will provide the background necessary to be able to understand and to work out the steps of conventional rigid method for mat analysis followed by a thorough review of previous work conducted in the fields touched on this thesis: conventional rigid method, the flexible method, and soil coefficient subgrade reactions were provided. In Chapter 3, a detailed description of suggested theoretical solutions of conventional rigid method noticed problems and it consists of three parts the first part applied modification factors only for columns load to construct the first suggested bending moment diagram trailed by a second solution used modifications only to the soil pressure to construct a second suggested bending moment diagram, and finally from the first and the second bending moments diagrams, an optimum average solution was proposed besides developing a user friendly computer structural analysis program by the researcher to analyze mat foundation strips using the proposed optimum solution by the researcher (third solution). Chapter 4 focused on the experimental test for different samples of sand to calculate the real values of coefficients subgrade reactions for the sandy soil and it supplied a comprehensive analysis for a number of reports of old plate load tests experiments done by material and soil laboratory of Islamic University of Gaza on sandy soil, the reports were divided into groups and a best fitting curve were obtained from each group followed by finding the best unified fitting curves for the best fitting curves of each group then developing a simplified relation to calculate the coefficient of subgrade reactions K of sandy soil as a function of known settlement and compared it to the Bowels relation (1997). Chapter 5 consisted of using two finite element analysis SAFE version 8 and SAP 2000 version 11 to confirm the use of the modified conventional rigid method suggested by the researcher to overcome the problems facing structural designers when constructing a bending moment shape using the conventional rigid method and to prove with evidence the possibility of applying a moment and shear reduction factor can be safely applied by an engineer. Chapter 6 comprised a scrupulous discussion of thesis findings and the last chapter contained a summary of the work, conclusions and recommendations.

7.2 Conclusions

Based on the findings of this report, the following conclusions were made:

- A modified rigid method for mat analysis suggested by the researcher has cracked down the problem of the conventional rigid method when constructing bending moment diagram for each individual strip for the mat by finding out a reasonable factors that made the resultant force of columns from top and the resultant force of the applied pressure under mat are equal and meet at the same line of action.

- A user friendly computer structural analysis program was developed by the researcher to analyze mat foundation strips using the proposed optimum solution by the researcher.

- The numerical values of the coefficient subgrade reactions obtained from the plate load test on sandy soil in Gaza were found relatively close to the values of the coefficients subgrade reactions suggested by Das (1999).

- A new relation has been carefully developed by the researcher to calculate the coefficient of subgrad reactions of sandy soil K_{mat} for mat foundation as a function of known mat settlement S_{mat} the relation is $K_{mat} = 2266- 23 (S_{mat})$ where K_{mat} unit in t/m^3 and S_{mat} unit in mm. It was also concluded that Bowels formula (1997) supplies large values of K in case of small settlement and this likely is because the pressure under small settlement is way less than the value of the ultimate bearing capacity however when considering large settlement it gives reasonable close values with those values calculated by the researcher relation because the value of the ultimate bearing capacity is close up to the pressure value around the large settlement

- It was shown that the moment values obtained from the modified conventional rigid method by the researcher are lower than the moment values obtained by the conventional rigid method and at the same time are higher than the moment values compared to moment values obtained from finite element out put of SAFE and Sap 2000 soft wares.

- It was shown that the shear force values obtained from the modified conventional rigid method by the researcher very much the same to the shear values obtained by the conventional rigid method and at the same time are higher than the shear force values compared to shear force values obtained from finite element output of SAFE and Sap 2000 soft wares.

- It was proven that a reduction of 15 percent in the moment values and 13 percent in the shear force values can be applied to the modified conventional rigid method suggested by the researcher for the two analyzed case studies of mat foundation within the research when it is compared to the moment and shear force values received from the finite element SAFE software.

- It was proven that a reduction between 20 and 18 percents in the moment values and between 15 and 10 percents in the shear force values can be applied to the modified conventional rigid method suggested by the researcher for the two analyzed case studies of mat foundation within the research when it is compared to the moment and shear force values received from the finite element Sap 2000 software.

7.3 Recommendations

During the course work of this thesis the researcher recommends the following suggestions for potential research in the area of modifying conventional rigid and flexible method of mat foundation design on sandy soil as follows:

- Performing an independent study of modifying conventional rigid and flexible method of mat foundation design on clayey and silty soil
- Developing new simplified relations to calculate the coefficient of subgrad reactions of clay and silt soil K_{mat} for mat foundation as a function of known mat settlement S_{mat}.
- Developing a comprehensive user friendly computer software structural analysis program to analyze mat foundation placed on different types of soil.
- Performing an independent study on the effect of thermal expansion and its contribution on different types of soil and mat foundation analysis.
- Checking the limit set by ACI committee 366 (1988) for the applicability for the modified conventional rigid method of different mat geometry configuration.

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Appendices

Appendix (A)

Design of mat Foundation (Figure 2.7)

First solution

Table (A.1): Shear and Moment numerical values for Strip ABMN

Strip ABMN

B1 = 3.0 m

B = 22.4 m

Column No.	Q'$_u$ (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	14.91	0.000			0.00
1	156.00			14.78	31.174	-124.826		10.93
		7	7.7				3.57	-166.99
5	314.40			13.44	171.501	-142.899		190.63
		7	14.7				11.34	-66.93
9	267.60			12.11	125.414	-142.186		145.78
		7	21.7				18.74	-138.46
13	120.60			10.78	98.111	-22.489		7.85
		0.7	22.4	10.64	0.000			0.00

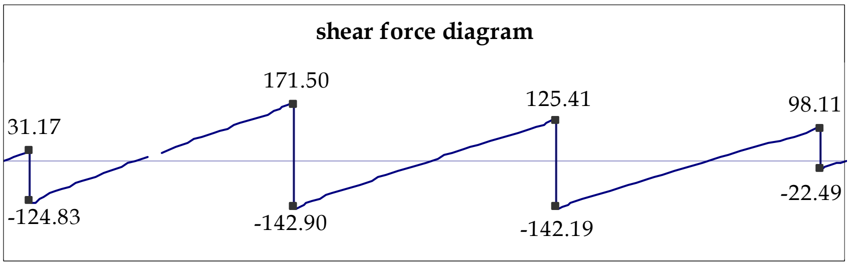

Figure (A.1): Shear force diagram for strips ABMN

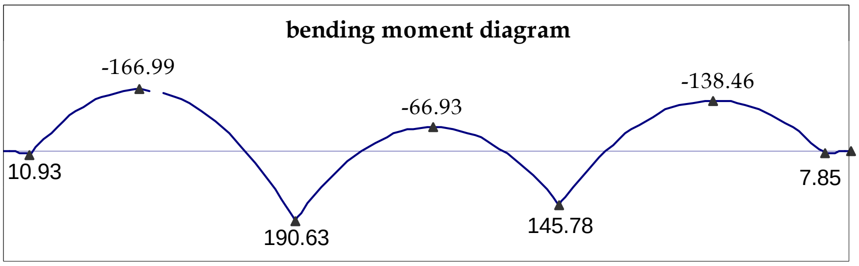

Figure (A.2): Moment diagram for strips ABMN

Table (A.2): Shear and Moment numerical values for Strip BDKM

Strip BDKM

B2 = 5.00 m

B = 22.40 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	18.26	0.000			
2	320.20			18.12	63.669	-256.531		22.31
		7	7.7				3.58	-344.99
6	646.20			16.65	351.859	-294.341		385.98
		7	14.7				11.32	-142.45
10	560.80			15.18	262.597	-298.203		304.88
		7	21.7				18.74	-292.10
14	255.00			13.71	207.281	-47.719		16.67
		0.7	22.4	13.56	0.000			0.00

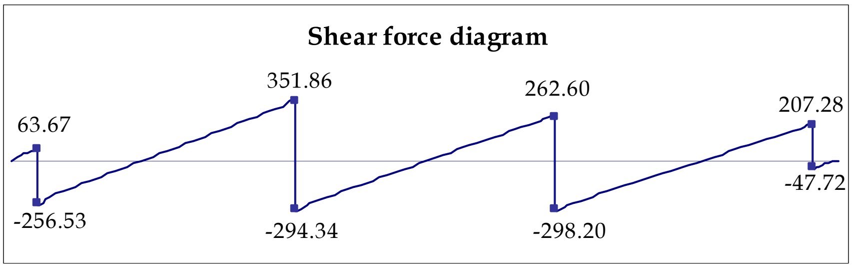

Figure (A.3): Shear force diagram for strips BDKM

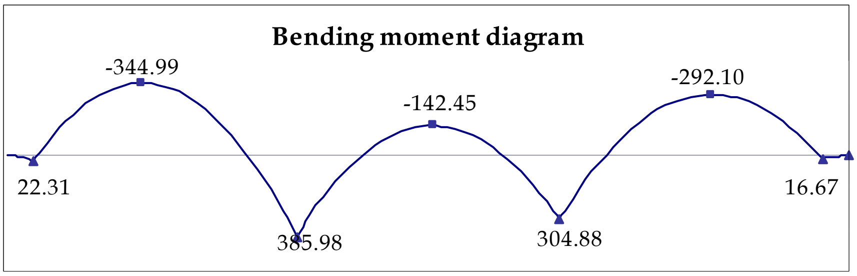

Figure (A.4):Moment diagram for strips BDKM

Table (A.3): Shear and Moment numerical values for Strip DFIK

Strip DFIK

B3 = 5.00 m

B = 22.40 m

Column No.	Q'$_u$ (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	16.12	0.000			
3	289.20			16.07	56.340	-232.860		19.73
		7	7.7				3.62	-319.10
7	590.60			15.58	320.972	-269.628		338.27
		7	14.7				11.19	-130.97
11	573.60			15.08	266.810	-306.790		338.56
		7	21.7				18.81	-289.70
15	263.20			14.58	212.252	-50.948		17.82
		0.7	22.4	14.53	0.000			0.00

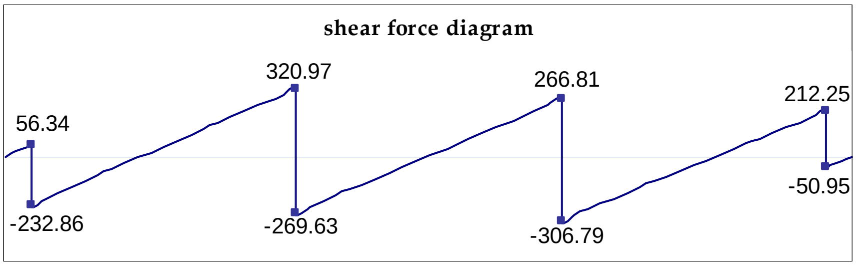

Figure (A.5): Shear force diagram for strips DFIK

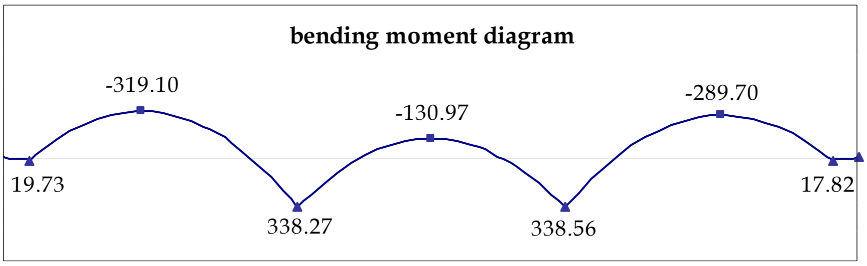

Figure (A.6): Moment diagram for strips DFIK

Table (A.4): Shear and Moment numerical values for Strip FGHI

Strip FGHI

B4 = 3.00 m	B = 22.40 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	12.46	0.000			
4	134.20			12.44	26.147	-108.053		9.15
		7	7.7				3.61	-147.79
8	276.60			12.16	150.233	-126.367		160.16
		7	14.7				11.18	-59.51
12	272.00			11.89	126.133	-145.867		162.72
		7	21.7				18.82	-137.00
16	125.20			11.61	100.847	-24.353		8.52
		0.7	22.4	11.58	0.000			0.00

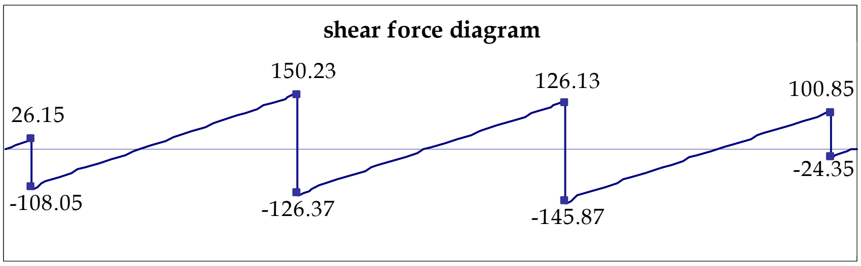

Figure (A.7): Shear force diagram for strips FGHI

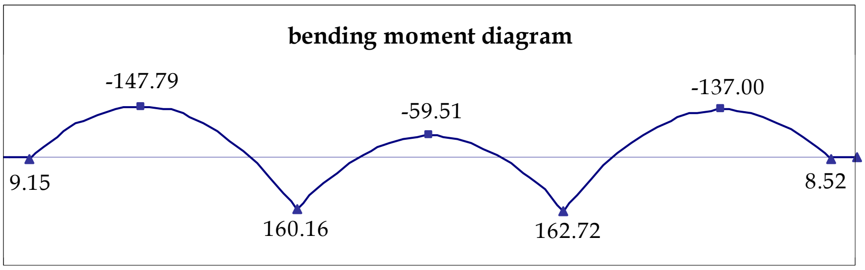

Figure (A.8): Moment diagram for strips FGHI

Second solution

Table (A.5): Shear and Moment numerical values for Strip ABMN

Strip ABMN

B1 = 3.0 m	B = 22.4 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	16.34	0.000			0.00
1	174.24			16.25	34.220	-140.021		11.99
		7	7.7				3.61	-190.69
5	351.16			15.33	191.589	-159.572		203.70
		7	14.7				11.22	-75.88
9	326.86			14.42	152.791	-174.065		191.20
		7	21.7				18.80	-163.48
13	147.30			13.50	119.052	-28.253		9.88
		0.7	22.4	13.41	0.000			0.00

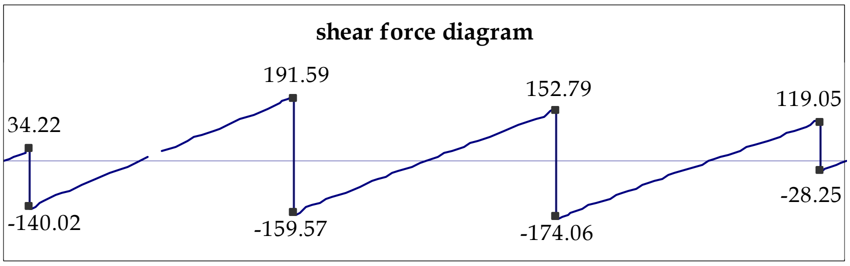

Figure (A.9): Shear force diagram for strips ABMN

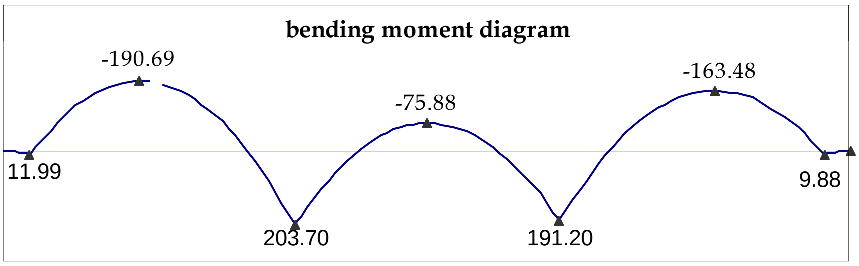

Figure (A.10): Moment diagram for strips ABMN

Table (A.6): Shear and Moment numerical values for Strip BDKM

Strip BDKM

B2 = 5.00 m   B = 22.40 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	16.06	0.000			
2	285.28			15.96	56.037	-229.243		19.63
		7	7.7				3.61	-312.17
6	575.73			15.05	313.489	-262.239		333.21
		7	14.7				11.24	-128.51
10	531.44			14.13	248.415	-283.021		303.53
		7	21.7				18.78	-270.49
14	241.65			13.22	195.555	-46.093		16.11
		0.7	22.4	13.12	0.000			0.00

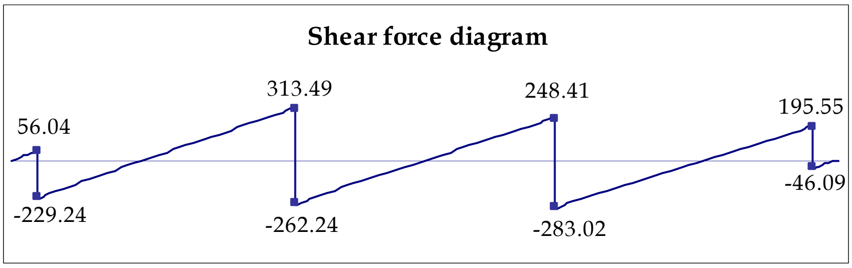

Figure (A.11): Shear force diagram for strips BDKM

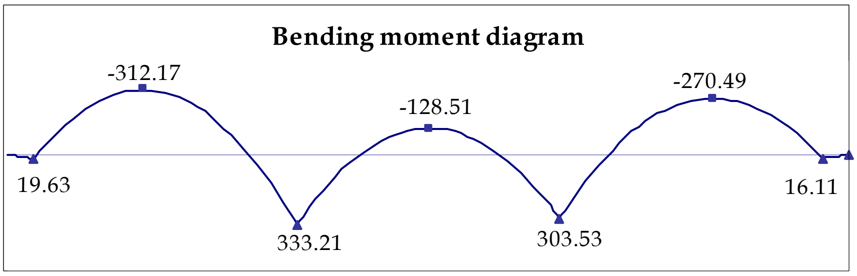

Figure (A.12):Moment diagram for strips BDKM

Table (A.7): Shear and Moment numerical values for Strip DFIK

Strip DFIK

B3 = 5.00 m

B = 22.40 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	15.70	0.000			
3	277.29			15.61	54.793	-222.497		19.20
		7	7.7				3.59	-300.53
7	566.28			14.69	307.795	-258.484		336.45
		7	14.7				11.28	-123.15
11	514.59			13.78	239.730	-274.862		289.52
		7	21.7				18.77	-266.01
15	236.12			12.86	191.274	-44.849		15.68
		0.7	22.4	12.77	0.000			0.00

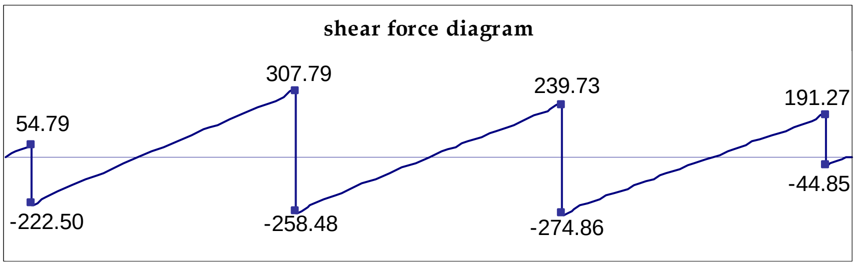

Figure (A.13): Shear force diagram for strips DFIK

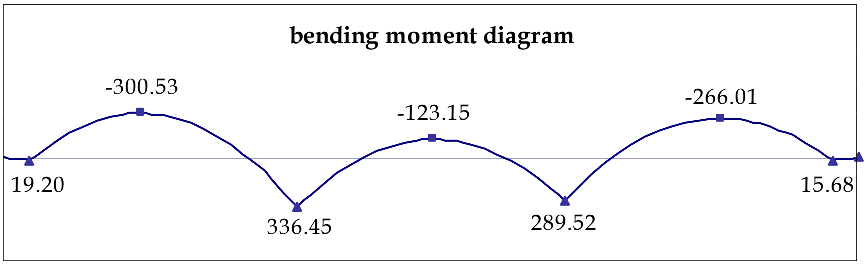

Figure (A.14): Moment diagram for strips DFIK

Table (A.8): Shear and Moment numerical values for Strip FGHI

Strip FGHI

B4 = 3.00 m

B = 22.40 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	15.42	0.000			
4	162.51			15.33	32.279	-130.233		11.31
		7	7.7				3.57	-174.66
8	334.95			14.41	181.971	-152.983		203.62
		7	14.7				11.30	-70.07
12	301.31			13.49	139.974	-161.333		169.32
		7	21.7				18.77	-156.48
16	138.69			12.58	112.377	-26.312		9.20
		0.7	22.4	12.48	0.000			0.00

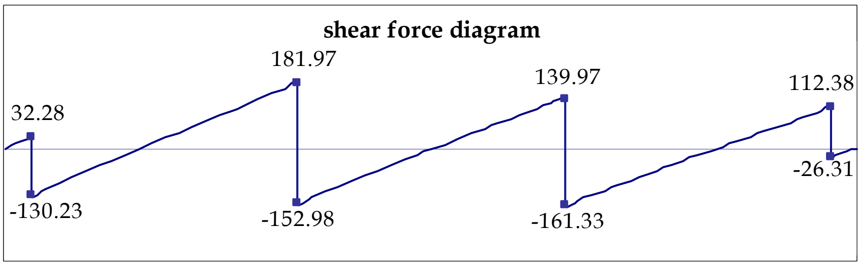

Figure (A.15): Shear force diagram for strips FGHI

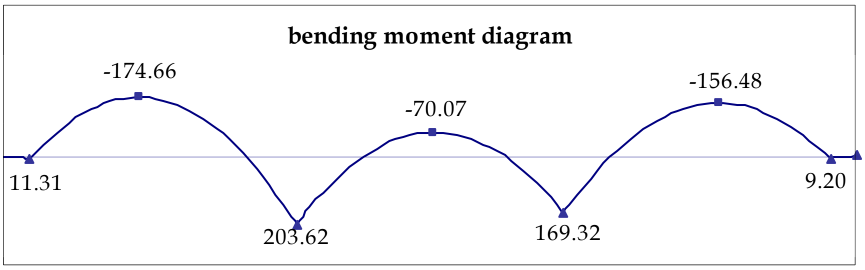

Figure (A.16): Moment diagram for strips FGHI

Third solution

Table (A.9): Shear and Moment numerical values for Strip ABMN

Strip ABMN

B1 = 3.0 m   B = 22.4 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	15.66	0.000			0.00
1	165.38			15.55	32.770	-132.610		11.48
		7	7.7				3.59	-178.96
5	333.30			14.40	181.830	-151.475		197.81
		7	14.7				11.28	-71.41
9	296.69			13.25	138.863	-157.825		167.73
		7	21.7				18.77	-150.87
13	133.71			12.10	108.411	-25.298		8.84
		0.7	22.4	11.99	0.000			0.00

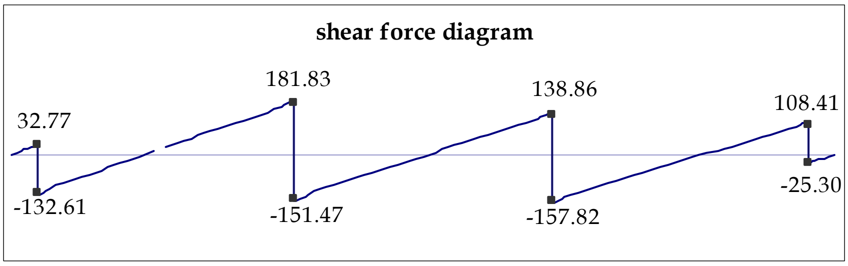

Figure (A.17): Shear force diagram for strips ABMN

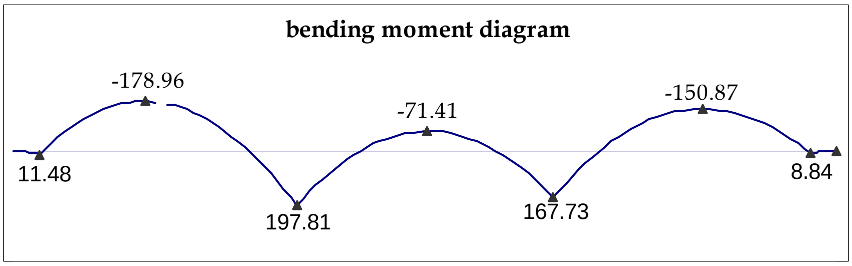

Figure (A.18): Moment diagram for strips ABMN

Table (A.10): Shear and Moment numerical values for Strip BDKM

Strip BDKM

B2 = 5.00 m

B = 22.40 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	17.14	0.000			
2	302.55			17.03	59.800	-242.752		20.95
		7	7.7				3.59	-328.48
6	610.58			15.84	332.467	-278.117		359.12
		7	14.7				11.28	-135.37
10	546.51			14.66	255.679	-290.830		304.75
		7	21.7				18.76	-281.34
14	248.50			13.48	201.543	-46.959		16.41
		0.7	22.4	13.36	0.000			0.00

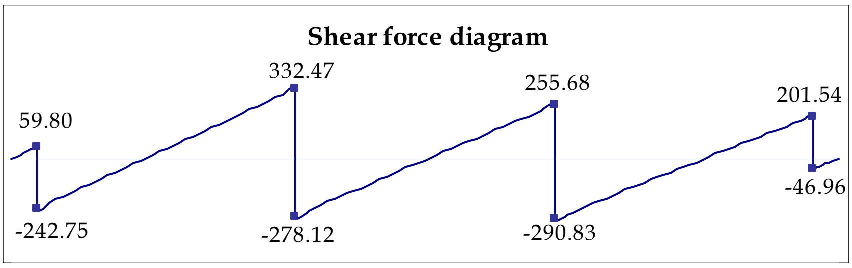

Figure (A.19): Shear force diagram for strips BDKM

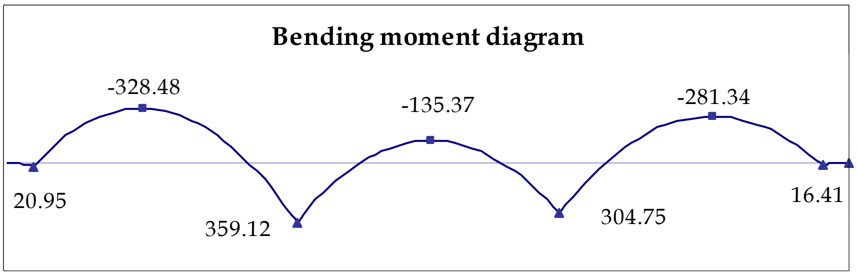

Figure (A.20):Moment diagram for strips BDKM

Table (A.11): Shear and Moment numerical values for Strip DFIK

Strip DFIK

B3 = 5.00 m

B = 22.40 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	15.93	0.000			
3	283.41			15.85	55.614	-227.798		19.48
		7	7.7				3.60	-309.88
7	578.78			15.14	314.569	-264.210		337.79
		7	14.7				11.23	-127.03
11	543.75			14.42	253.115	-290.633		313.56
		7	21.7				18.79	-277.78
15	249.50			13.71	201.651	-47.851		16.73
		0.7	22.4	13.64	0.000			0.00

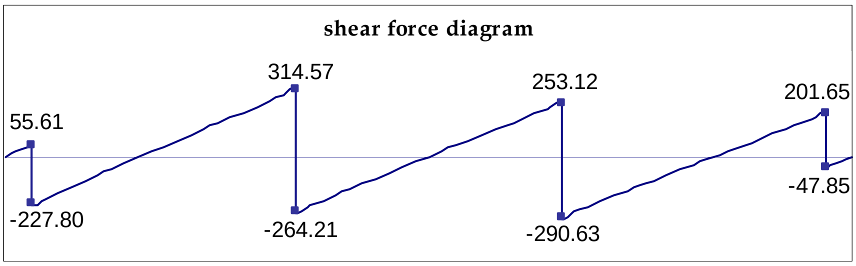

Figure (A.21): Shear force diagram for strips DFIK

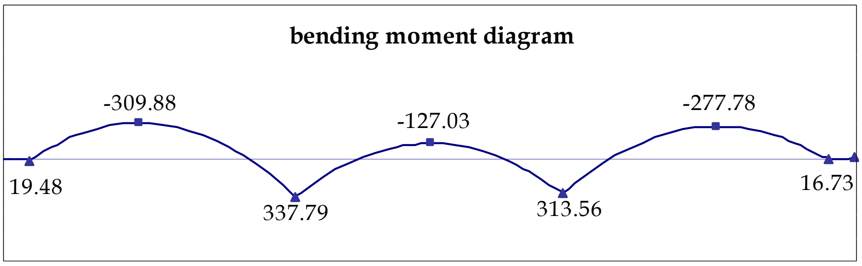

Figure (A.22): Moment diagram for strips DFIK

Table (A.12): Shear and Moment numerical values for Strip FGHI

Strip FGHI

B4 = 3.00 m	B = 22.40 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		0.7	0.7	13.91	0.000			
4	148.12			13.85	29.146	-118.975		10.21
		7	7.7				3.59	-161.10
8	305.29			13.27	165.837	-139.455		181.27
		7	14.7				11.24	-64.69
12	287.15			12.70	133.273	-153.873		166.69
		7	21.7				18.79	-146.81
16	132.17			12.12	106.772	-25.400		8.88
		0.7	22.4	12.07	0.000			0.00

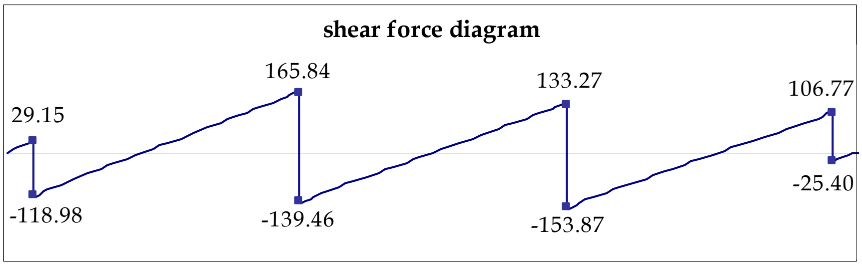

Figure (A.23): Shear force diagram for strips FGHI

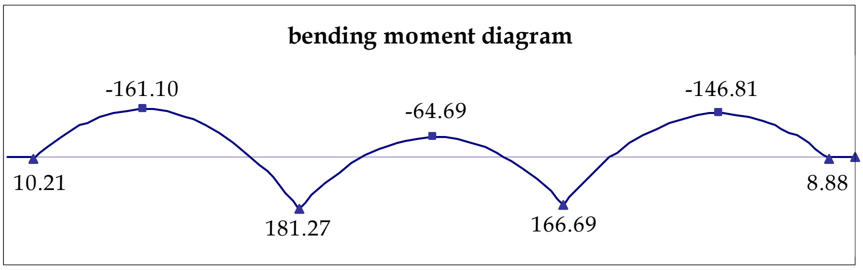

Figure (A.24): Moment diagram for strips FGHI

Appendix (B)

Design of mat L-Shape using the third suggestion recommended by the researcher.

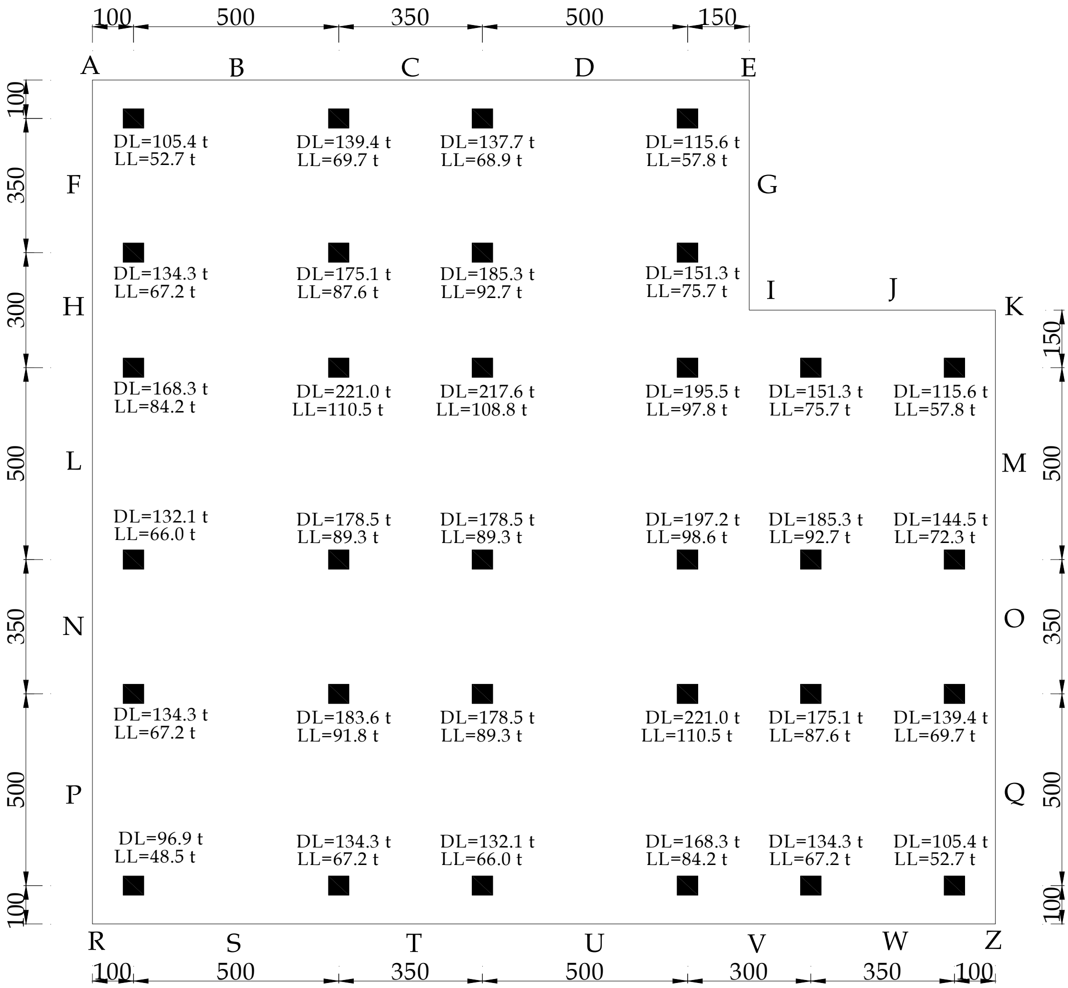

Figure (B.1): Layout of L shape mat foundation

Step 1: check soil pressure for selected dimensions

Column service loads = Σ Qi (where i = 1 to n)

According to ACI 318-05 (Section 9.2),

Factored load, U = 1.2 (Dead load) + 1.6 (Live load)

So, Ultimate load $Q_u = \Sigma [1.2 DL_i + 1.6LL_i]$

Ultimate to service load ratio $r_u = Q_u/Q$

The Table (B.1) shows the calculation for the loads:

Table (B.1): Load calculations

Column No.	DL (ton)	LL (ton)	Q (ton)	Q_u (ton)
1	88.5	44.2	132.7	176.9
2	118.9	59.5	178.4	237.8
3	117.5	58.7	176.2	234.9
4	98.6	49.3	147.9	197.2
5	108.8	54.4	163.1	217.5
6	149.4	74.7	224.0	298.7
7	158.1	79.0	237.1	316.1
8	129.1	64.5	193.6	258.1
9	132.0	66.0	197.9	263.9
10	188.5	94.3	282.8	377.0
11	185.6	92.8	278.4	371.2
12	166.8	83.4	250.1	333.5
13	129.1	64.5	193.6	258.1
14	98.6	49.3	147.9	197.2
15	104.4	52.2	156.6	208.8
16	152.3	76.1	228.4	304.5
17	152.3	76.1	228.4	304.5
18	168.2	84.1	252.3	336.4
19	158.1	79.0	237.1	316.1
20	123.3	61.6	184.9	246.5
21	108.8	54.4	163.1	217.5
22	156.6	78.3	234.9	313.2
23	152.3	76.1	228.4	304.5
24	188.5	94.3	282.8	377.0
25	149.4	74.7	224.0	298.7
26	118.9	59.5	178.4	237.8
27	73.2	36.6	109.8	146.5
28	108.8	54.4	163.1	217.5
29	104.4	52.2	156.6	208.8
30	132.0	66.0	197.9	263.9
31	108.8	54.4	163.1	217.5
32	88.5	44.2	132.7	176.9
		Total Loads =	6326.0	8434.7
		r_u =	1.333	

Ultimate pressure $q_u = q_a \times r_u = 18 \times 1.333 = 22.54$ t/m^2

Center of Gravity of Base

$X_{centroid}$ of L shape mat foundation = 10.357 m

$Y_{centroid}$ of L shape mat foundation = 10.357 m

Location of the resultant load Q,

In x- direction

Moment summation is $\Sigma M_{y\text{-axis}} = 0.0$ (see table B.2)

Table (B.2): Moment calculation in x- direction

Q (ton)	Q_u (ton)	X_i (m)	M (t.m)	M_u (t.m)
132.7	176.9	1	132.7	176.9
178.4	237.8	6	1070.1	1426.8
176.2	234.9	9.5	1673.7	2231.6
147.9	197.2	14.5	2144.6	2859.4
163.1	217.5	1	163.1	217.5
224.0	298.7	6	1344.2	1792.2
237.1	316.1	9.5	2252.2	3003.0
193.6	258.1	14.5	2806.8	3742.5
197.9	263.9	1	197.9	263.9
282.8	377.0	6	1696.5	2262.0
278.4	371.2	9.5	2644.8	3526.4
250.1	333.5	14.5	3626.8	4835.8
193.6	258.1	17.5	3387.6	4516.8
147.9	197.2	21	3105.9	4141.2
156.6	208.8	1	156.6	208.8
228.4	304.5	6	1370.3	1827.0
228.4	304.5	9.5	2169.6	2892.8
252.3	336.4	14.5	3658.4	4877.8
237.1	316.1	17.5	4148.8	5531.8
184.9	246.5	21	3882.4	5176.5
163.1	217.5	1	163.1	217.5
234.9	313.2	6	1409.4	1879.2
228.4	304.5	9.5	2169.6	2892.8
282.8	377.0	14.5	4099.9	5466.5
224.0	298.7	17.5	3920.4	5227.3
178.4	237.8	21	3745.4	4993.8
109.8	146.5	1	109.8	146.5
163.1	217.5	6	978.8	1305.0
156.6	208.8	9.5	1487.7	1983.6
197.9	263.9	14.5	2869.9	3826.6
163.1	217.5	17.5	2854.7	3806.3
132.7	176.9	21	2786.2	3714.9
		$\Sigma Q_i . X_i =$	68227.6	90970.1

$X_{bar} = [\Sigma Q_i \ X_i]/ \Sigma Q_i = 68{,}227.6/6325.99 = 10.79$ m

$e_x = X_{bar} - X_{centroid} = 10.79 - 10.375 = 0.43$ m

In y- direction

Moment summation is $\Sigma M_{x\text{-axis}} = 0.0$ (see table B.3)

Table (B.3): Moment calculation in Y direction

Q (ton)	Q_u (ton)	X_i (m)	M (t.m)	M_u (t.m)
132.7	176.9	21	2786.2	3714.9
178.4	237.8	21	3745.4	4993.8
176.2	234.9	21	3699.7	4932.9
147.9	197.2	21	3105.9	4141.2
163.1	217.5	17.5	2854.7	3806.3
224.0	298.7	17.5	3920.4	5227.3
237.1	316.1	17.5	4148.8	5531.8
193.6	258.1	17.5	3387.6	4516.8
197.9	263.9	14.5	2869.9	3826.6
282.8	377.0	14.5	4099.9	5466.5
278.4	371.2	14.5	4036.8	5382.4
250.1	333.5	14.5	3626.8	4835.8
193.6	258.1	14.5	2806.8	3742.5
147.9	197.2	14.5	2144.6	2859.4
156.6	208.8	9.5	1487.7	1983.6
228.4	304.5	9.5	2169.6	2892.8
228.4	304.5	9.5	2169.6	2892.8
252.3	336.4	9.5	2396.9	3195.8
237.1	316.1	9.5	2252.2	3003.0
184.9	246.5	9.5	1756.3	2341.8
163.1	217.5	6	978.8	1305.0
234.9	313.2	6	1409.4	1879.2
228.4	304.5	6	1370.3	1827.0
282.8	377.0	6	1696.5	2262.0
224.0	298.7	6	1344.2	1792.2
178.4	237.8	6	1070.1	1426.8
109.8	146.5	1	109.8	146.5
163.1	217.5	1	163.1	217.5
156.6	208.8	1	156.6	208.8
197.9	263.9	1	197.9	263.9
163.1	217.5	1	163.1	217.5
132.7	176.9	1	132.7	176.9
		$\Sigma Q_i . Y_i =$	68227.6	90970.1

$Y_{bar} = [\Sigma Q_i \; y_i]/ \Sigma Q_i = 68,227.6/6325.99 = 10.79$ m

$e_y = Y_{bar} - Y_{centroid} = 10.79 - 10.375 = 0.43$ m

Applied ultimate pressure, $q = \left[\frac{Q}{A} \pm \frac{M_y \, x}{I_y} \pm \frac{M_x \, y}{I_x} \right]$

Where: A = Base area = (22.0*22.0)-(6.0*6.0) = 448.00 m^2

$M_{u,x} = Q_u \, e_y$ = 8,434.7* 0.43 = 3,626.9 t. m

$M_{u,y} = Q_u \, e_x$ = 8,434.7* 0.43 = 3,626.9 t. m

$$I_x = \left(\frac{B L^3}{12} + AD^2 \right) - \left(\frac{b l^3}{12} + a d^2 \right) = 16924.19 \text{ m}^4$$

$$I_y = \left(\frac{B^3 L}{12} + AD^2 \right) - \left(\frac{b^3 l}{12} + a d^2 \right) = 16924.19 \text{m}^4$$

Therefore, $q_{u,applied} = \left[\frac{8{,}434.7}{448.0} \pm \frac{3{,}626.9 \, x}{16924.19} \pm \frac{3{,}626.9 \, y}{16924.19} \right]$

$$= 18.83 \; \pm \; 0.214 \, x \; \pm \; 0.214 \, y \qquad (t/m^2)$$

Now stresses can be summarized (see table B.4)

Table (B.4): Allowable stresses calculations

Point	Q/A (t/m²)	x (m)	+ 0.214 X (t/m²)	y (m)	+ 0.214 Y (t/m²)	q (t/m²)
A	18.83	-10.36	-2.22	11.64	2.50	19.10
B	18.83	-6.86	-1.47	11.64	2.50	19.85
C	18.83	-2.61	-0.56	11.64	2.50	20.76
D	18.83	-22.36	-4.79	11.64	2.50	16.53
E	18.83	5.64	1.21	11.64	2.50	22.53
F	18.83	-10.36	-2.22	8.89	1.91	18.51
G	18.83	5.64	1.21	8.89	1.91	21.94
H	18.83	-10.36	-2.22	5.64	1.21	17.82
I	18.83	5.64	1.21	5.64	1.21	21.25
J	18.83	8.89	1.91	5.64	1.21	21.94
K	18.83	11.64	2.50	5.64	1.21	22.53
L	18.83	-10.36	-2.22	1.64	0.35	16.96
M	18.83	11.64	2.50	1.64	0.35	21.67
N	18.83	-10.36	-2.22	-2.61	-0.56	16.05
O	18.83	11.64	2.50	-2.61	-0.56	20.76
P	18.83	-10.36	-2.22	-6.86	-1.47	15.14
Q	18.83	11.64	2.50	-6.86	-1.47	19.85
R	18.83	-10.36	-2.22	-10.36	-2.22	14.39
S	18.83	-6.86	-1.47	-10.36	-2.22	15.14
T	18.83	-2.61	-0.56	-10.36	-2.22	16.05
U	18.83	1.64	0.35	-10.36	-2.22	16.96
V	18.83	5.64	1.21	-10.36	-2.22	17.82
W	18.83	8.89	1.91	-10.36	-2.22	18.51
Z	18.83	11.64	2.50	-10.36	-2.22	19.10

The soil pressures at all points are less than the ultimate pressure = 24.00 t/m^2

Step 2- Draw shear and moment diagrams

The mat is divided into several strips in long direction and the following strips are considered: ABST, BCTS, CDUT, DEVU, IJWV and JKZW in the analysis. The following calculations are performed for every strip:

B) The average uniform soil reaction,

$$q_u = \frac{q_{u,Edge1} + q_{u,Edge2}}{2}$$

refer to the previous table for pressure values

for Strip ABSR (width = 3.50 m)

$q_{u,Edge1} = 19.50\ t/m^2$

$q_{u,Edge2} = 14.76\ t/m^2$

for Strip BCTS (width = 4.25 m)

$q_{u,Edge1} = 20.33\ t/m^2$

$q_{u,Edge2} = 15.58\ t/m^2$

for Strip CDUT (width = 4.25 m)

$q_{u,Edge1} = 18.68\ t/m^2$

$q_{u,Edge2} = 16.49\ t/m^2$

for Strip DEVU (width = 4.00 m)

$q_{u,Edge1} = 19.56\ t/m^2$

$q_{u,Edge2} = 17.37\,t/m^2$

for Strip IJWV (width = 3.25 m)

$q_{u,Edge1} = 21.60\ t/m^2$

$q_{u,Edge2} = 18.14\,t/m^2$

for Strip JKZW (width = 2.75 m)

$q_{u,Edge1} = 22.24\ t/m^2$

$q_{u,Edge2} = 18.78\,t/m^2$

B) Total soil reaction qu,avg x (Bi x B)

Strip ABSR : B_1= 3.50 m

Strip BCTS : B_2= 4.25 m

Strip CDUT : B_3= 4.25 m

Strip DEVU : B_4= 4.00 m

Strip IJWV : B_5= 3.25 m

Strip JKZW : B_6= 2.75 m

For strips ABST, BCTS, CDUT, and DEVU : B = 22 m

For strips IJWV and JKZW : B = 16.0 m

C) Total column loads $Q_{u,total} = \Sigma$ Qui locates @ distance X_{load}

D) Total soil pressure, $q_{u,avg}$ Bi B locates @ distance $X_{pressure}$

E) $\text{Average load} = \dfrac{q_{u,avg} x(B_i\ B) + Q_{u,total}}{2}$

locates @ distance $X_{average} = \dfrac{X_{Load} + X_{Pressure}}{2}$

F) Modified Column Loads

All columns loads at the left of the average load are multiplied with F1 and all columns loads at the right of the average load are multiplied with F2.

$$\sum F_x = 0.0$$

$$F_1 \sum Q_{Left} + F_2 \sum Q_{Right} = \text{Average load} \quad \Rightarrow \text{eq.}1$$

$$\sum M_{\text{at left point}} = 0.0$$

$$F_1 \sum (Q_{i\,Left} \cdot x_i) + F_2 \sum (Q_{i\,Right} \cdot x_i) = \text{Average load} \cdot X_{pressure} \quad \Rightarrow \text{eq.}2$$

from equation eq. 1 & eq. 2 we get F_1 and F_2, and

Modified Loads on strip

$Q_{ui\ Left}$ = F_1 x $Q_{ui\ Left}$

$Q_{ui\ Right}$ = F_2 x $Q_{ui\ Right}$

Modified Soil Pressure

$$X_{average} = \frac{(2\,q_{u,2\,mod} + q_{u,1\,mod})B}{3(q_{u,1\,mod} + q_{u,2\,mod})} \quad \Rightarrow \text{eq.}3$$

Where, $\left(\dfrac{q_{u,1mod} + q_{u,1mod}}{2}\right) B\,B_i = \text{Average load} \quad \Rightarrow \text{eq.}4$

from eq. 3 & eq. 4 we get $q_{u,1mod}$ and $q_{u,2mod}$

The calculations for the selected strips are summarized in Table B.5

Table (B.6): Summarized calculations of the selected strips

Strip	B_i (m)	Point	q_{Edge} (t/m^2)	q_{avg} (t/m^2)	$q_{avg}\ B_i\ B$ (tons)	$Q_{u,total}$ (tons)	Average Load (tons)	$q_{avg,mod}$ (t/m^2)	Factor
ABSR	3.5	A,B	19.48	17.12	1318.29	1231.05	1274.67	19.970	F1=0.992
		S,R	14.76		@ xp =10.50	@ xp =9.99	@ xp =10.24	13.138	F2=1.085
BCTS	4.25	B,C	20.31	17.95	1678.42	1748.70	1713.56	21.590	F1=0.951
		T,S	15.59		@ xp =10.52	@ xp =10.18	@ xp =10.35	15.064	F2=1.011
CDUT	4.25	C,D	18.65	17.58	1643.35	1740.00	1691.68	20.963	F1=0.913
		U,T	16.50		@ xp =10.78	@ xp =10.06	@ xp =10.42	15.222	F2=1.039
DEVU	4	D'E	19.53	18.46	1624.48	1766.10	1695.29	19.509	F1=0.992
		V,U	17.39		@ xp =10.79	@ xp =11.12	@ xp =10.95	19.020	F2=0.934
IJWV	3.25	I,J	21.59	19.88	1033.74	1090.40	1062.07	21.417	F1=0.998
		W,V	18.17		@ xp =7.77	@ xp =7.97	@ xp =7.87	19.432	F2=0.948
JKZW	2.75	J,K	22.24	20.52	902.99	858.40	880.70	20.579	F1=1.063
		Z,W	18.81		@ xp =7.78	@ xp =8.07	@ xp =7.92	19.452	F2=0.986

Based on Table (B.5), the adjusted column loads and pressure under each strip are represented in Table (B.6) through Table (B.11):

Table (B.6): Strip ABSR allowable stress calculations

Column No.	Qu, (ton)	Xi, (m)	load left (ton)	load right (ton)	Factors	Q'u, (ton)	qu,mod ton/m^2
1	176.9	1	176.9	0	F1=0.992	175.50	q1 =19.97
5	217.5	4.5	217.5	0		215.78	
9	263.9	7.5	263.9	0		261.81	
15	208.8	12.5	0	208.8	F2=1.085	226.60	q2 =13.14
21	217.5	16	0	217.5		236.05	
27	146.45	21	0	146.45		158.94	
Total =	1231.05		658.3 F1	572.8 F2		1274.67	
			3134.90 F1	9165.45 F2			

Table (B.7): Strip BCTS allowable stress calculations

Column No.	Qu, (ton)	Xi, (m)	load left (ton)	load right (ton)	Factors	Q'u, (ton)	qu,mod ton/m^2
2	237.8	1	237.8	0	F1=0.951	226.20	q1 =21.59
6	298.7	4.5	298.7	0		284.12	
10	377	7.5	377	0		358.60	
16	304.5	12.5	0	304.5	F2=1.011	307.94	q2 =15.06
22	313.2	16	0	313.2		316.74	
28	217.5	21	0	217.5		219.96	
Total =	1748.7		913.5 F1	835.2 F2		1713.56	
			4409.45 F1	13384.95 F2			

Table (B.8): Strip CDUT allowable stress calculations

Column No.	Qu, (ton)	Xi, (m)	load left (ton)	load right (ton)	Factors	Q'u, (ton)	qu,mod ton/m^2
3	234.9	1	234.9	0	F1=0.913	214.54	q1 =20.96
7	316.1	4.5	316.1	0		288.70	
11	371.2	7.5	371.2	0		339.03	
17	304.5	12.5	0	304.5	F2=1.039	316.27	q2 =15.22
23	304.5	16	0	304.5		316.27	
29	208.8	21	0	208.8		216.87	
Total =	1740		922.2 F1	817.8 F2		1691.68	
			4441.35 F1	13063.05 F2			

Table (B.9): Strip DEVU allowable stress calculations

Column No.	Qu, (ton)	Xi, (m)	load left (ton)	load right (ton)	Factors	Q'u, (ton)	qu,mod ton/m^2
4	197.2	1	197.2	0	F1=0.992	195.56	q1 =19.51
8	258.1	4.5	258.1	0		255.95	
12	333.5	7.5	333.5	0		330.72	
18	336.4	12.5	0	336.4	F2=0.934	314.29	q2 =19.02
24	377	16	0	377		352.22	
30	263.9	21	0	263.9		246.55	
Total =	1766.1		788.8 F1	977.3 F2		1695.29	
			3859.90 F1	15778.90 F2			

Table (B.10): Strip IJWV allowable stress calculations

Column No.	Qu, (ton)	Xi, (m)	load left (ton)	load right (ton)	Factors	Q'u, (ton)	qu,mod ton/m^2
13	258.1	1.5	258.1	0	F1=0.998	257.49	q1 =21.42
19	316.1	6.5	316.1	0		315.36	
25	298.7	10	0	298.7	F2=0.948	283.09	q2 =19.43
31	217.5	15	0	217.5		206.13	
Total =	1090.4		574.2 F1	516.2 F2		1062.07	
			2441.80 F1	6249.50 F2			

Table (B.11): Strip JKZW allowable stress calculations

Column No.	Qu, (ton)	Xi, (m)	load left (ton)	load right (ton)	Factors	Q'u, (ton)	qu,mod ton/m^2
14	197.2	1.5	197.2	0	F1=1.063	209.68	q1 =20.58
20	246.5	6.5	246.5	0		262.10	
26	237.8	10	0	237.8	F2=0.986	234.48	q2 =19.45
32	176.9	15	0	176.9		174.43	
Total =	858.4		443.7 F1	414.7 F2		880.70	
			1898.05 F1	5031.50 F2			

Tables (B.12) through (B.17) and the Figures (B.2) to (B.13) represents the shear and moment numerical values and the construction of shear force diagram and the bending moment diagrams for the four different strips.

Table (B.12): Shear and Moment numerical values for Strip ABSR

Strip ABSR

B1 = 3.50 m

B = 22.0 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		1	1	19.97	0.000			0.00
1	175.50			19.66	69.351	-106.147		34.77
		3.5	4.5				2.56	-47.79
5	215.78			18.57	128.022	-87.754		76.93
		3	7.5				5.87	17.24
9	261.81			17.64	102.366	-159.442		101.29
		5	12.5				10.14	-107.80
15	226.60			16.09	135.689	-90.914		53.23
		3.5	16				14.14	-20.94
21	236.05			15.00	99.512	-136.533		72.16
		5	21				18.67	-108.68
27	158.94			13.45	112.409	-46.528		23.17
		1	22	13.14	0.000			0.00

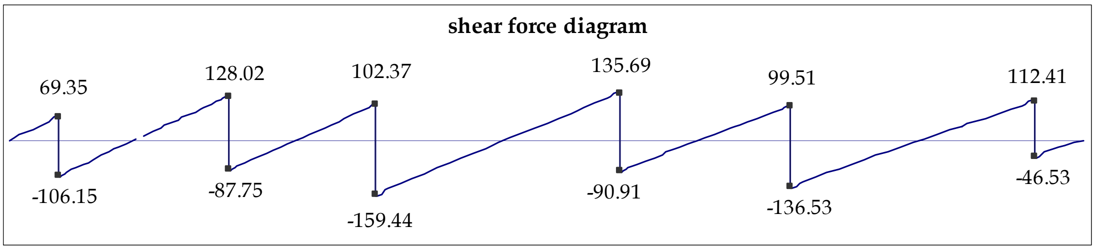

Figure (B.2): Shear force diagram for strip ABST

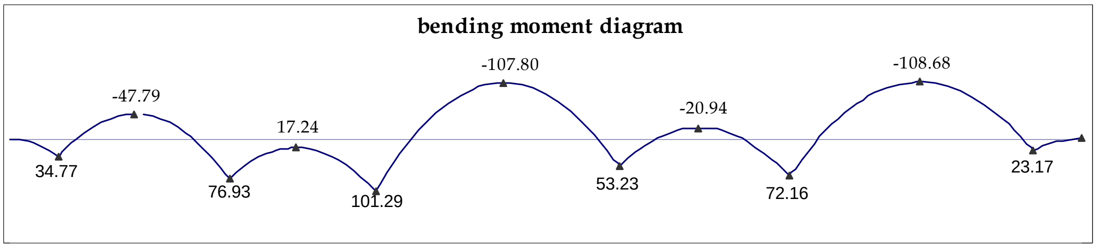

Figure (B.3): Moment diagram for strip ABST

Table (B.13): Shear and Moment numerical values for Strip BCTS

Strip BCTS

B2 = 4.25 m

B = 22.0 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		1	1	21.59	0.000			0.00
2	226.20			21.29	91.127	-135.069		45.67
		3.5	4.5				2.51	-55.84
6	284.12			20.26	173.947	-110.177		118.21
		3	7.5				5.79	47.26
10	358.60			19.37	142.401	-216.203		169.38
		5	12.5				10.18	-118.52
16	307.94			17.88	179.547	-128.393		90.87
		3.5	16				14.21	-18.62
22	316.74			16.84	129.877	-186.861		97.98
		5	21				18.67	-149.78
28	219.96			15.36	155.306	-64.651		32.22
		1	22	15.06	0.000			0.00

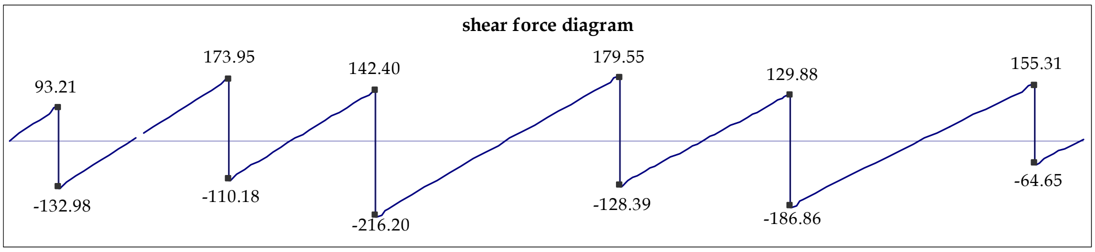

Figure (B.4): Shear force diagram for strip BCTS

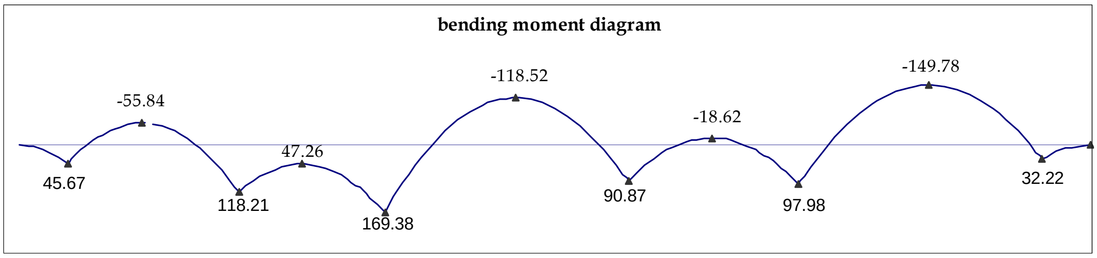

Figure (B.5): Moment diagram for strip BCTS

Table (B.14): Shear and Moment numerical values for Strip CDUT

Strip CDUT

B2 = 4.25 m | B = 22.0 m

Column No.	Q'$_u$ (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		1	1	20.96	0.000			0.00
3	214.54			20.70	88.540	-126.001		44.36
		3.5	4.5				2.45	-46.41
7	288.70			19.79	175.155	-113.549		134.34
		3	7.5				5.86	57.23
11	339.03			19.01	133.771	-205.257		167.17
		5	12.5				10.09	-96.73
17	316.27			17.70	184.761	-131.507		127.49
		3.5	16				14.27	11.54
23	316.27			16.79	125.008	-191.260		120.08
		5	21				18.74	-139.95
29	216.87			15.48	151.620	-65.249		32.53
		1	22	15.22	0.000			0.00

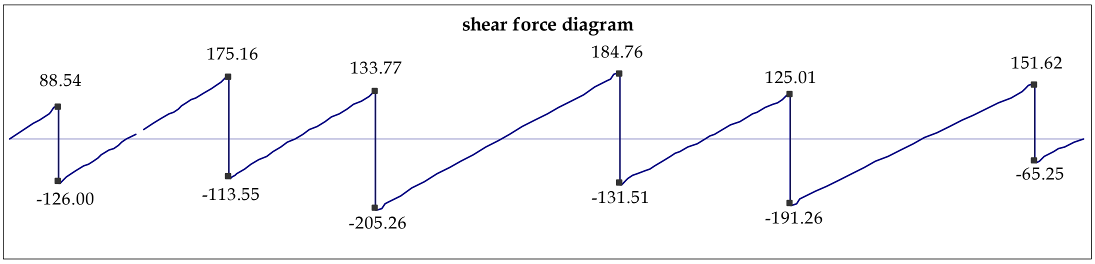

Figure (B.6): Shear force diagram for strip CDUT

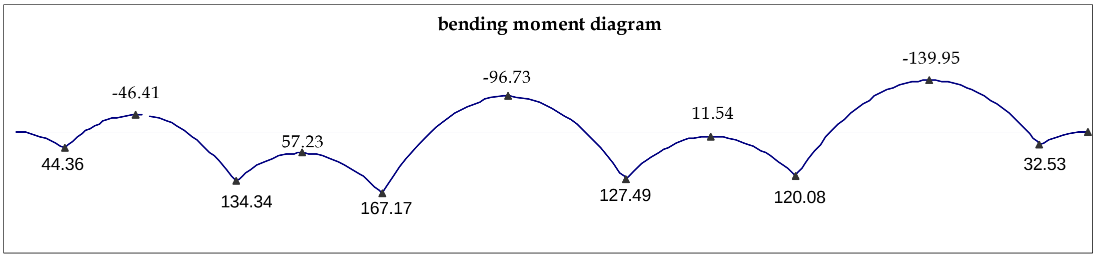

Figure (B.7): Moment diagram for strip CDUT

Table (B.15): Shear and Moment numerical values for Strip DEVU

Strip DEVU

B2 = 4.00 m

B = 22.0 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		1	1	19.51	0.000			0.00
4	195.56			19.49	77.991	-117.568		39.00
		3.5	4.5				2.51	-49.71
8	255.95			19.41	154.701	-101.251		104.30
		3	7.5				5.81	38.25
12	330.72			19.34	131.257	-199.468		149.51
		5	12.5				10.08	-107.87
18	314.29			19.23	186.269	-128.017		117.44
		3.5	16				14.17	10.85
24	352.22			19.15	140.678	-211.538		139.91
		5	21				18.77	-152.43
30	246.55			19.04	170.425	-76.126		38.06
		1	22	19.02	0.000			0.00

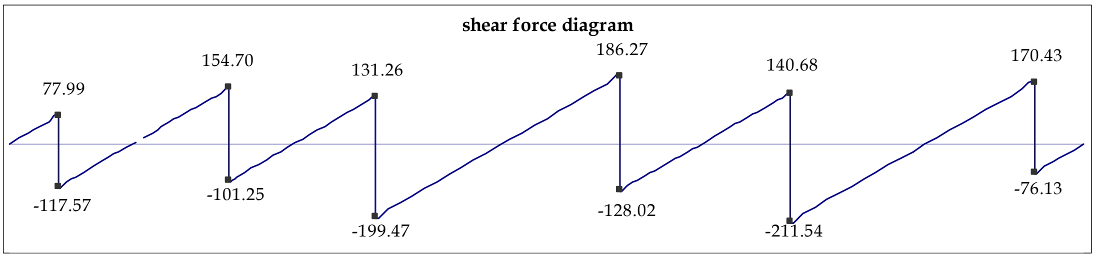

Figure (B.8): Shear force diagram for strip DEVU

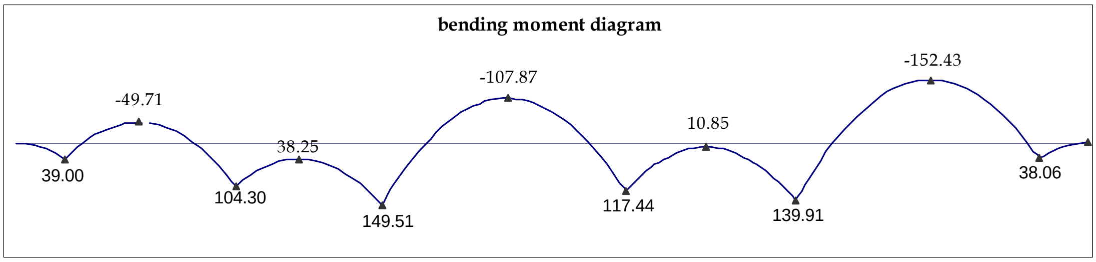

Figure (B.9): Moment diagram for strip DEVU

Table (B.16): Shear and Moment numerical values for Strip IJWV

Strip IJWV

B2 = 3.25 m

B = 16.0 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m^2)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		1.5	1.5	21.42	0.000			0.00
13	257.49			21.23	103.955	-153.540		78.08
		5	6.5				3.74	-93.49
19	315.36			20.61	186.424	-128.935		164.49
		3.5	10				8.44	39.92
25	283.09			20.18	103.041	-180.047		120.62
		5	15				12.77	-127.97
31	206.13			19.56	142.777	-63.355		31.64
		1	16	19.43	0.000			0.00

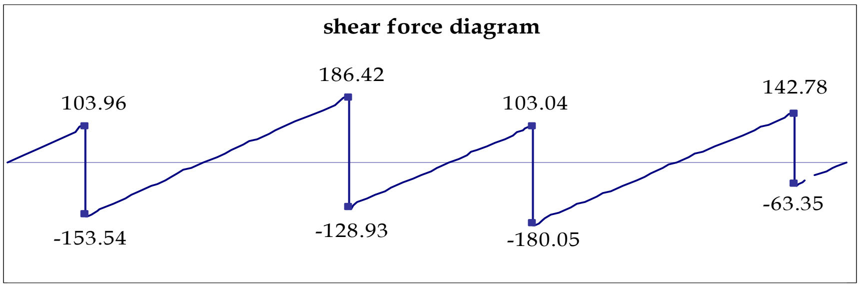

Figure (B.10): Shear force diagram for strip IJWV

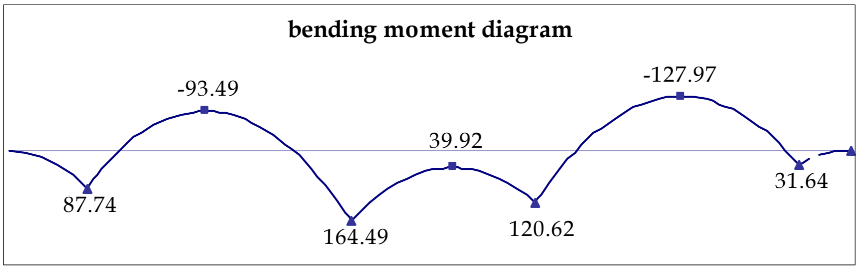

Figure (B.11): Moment diagram for strip IJWV

Table (B.17): Shear and Moment numerical values for Strip JKZW

Strip JKZW

B2 = 2.75 m

B = 16.0 m

Column No.	Q'u (ton)	Span Length (m)	Distance (m)	$q_{avg,mod}$ (t/m²)	shear Left (ton)	shear Right (ton)	x @ V=0.0 (m)	Moment (t.m)
		1.5	1.5	20.58	0.000			0.00
14	209.68			20.47	84.672	-125.011		63.56
		5	6.5				3.73	-75.58
20	262.10			20.12	154.081	-108.022		138.25
		3.5	10				8.46	32.57
26	234.48			19.87	84.461	-150.020		97.71
		5	15				12.76	-108.85
32	174.43			19.52	120.840	-53.591		26.78
		1	16	19.45	0.000			0.00

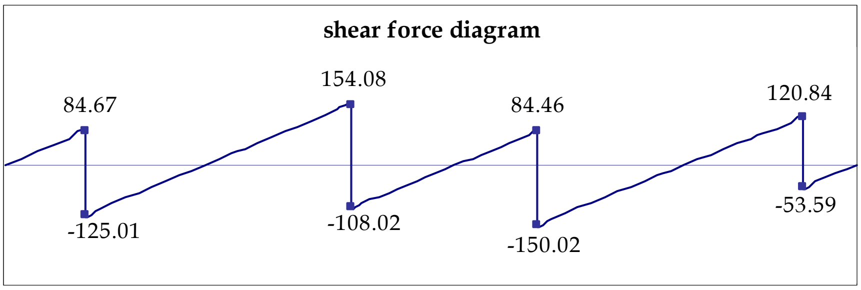

Figure (B.12): Shear force diagram for strip JKZW

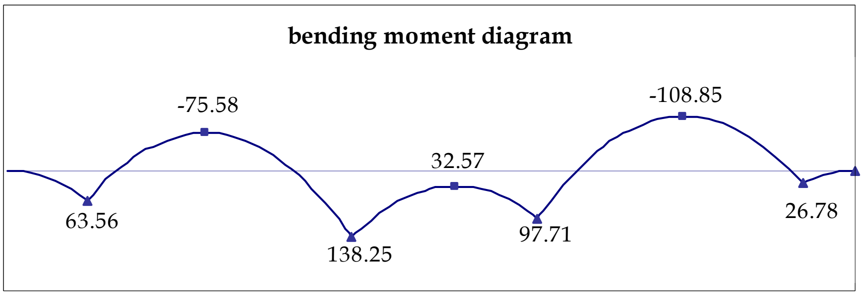

Figure (B.13): Moment diagram for strip JKZW

Appendix (C)

Bearing Capacity Calculation

It should be noticed that the load test may express only the short term loading of a small plate and not the long term loading of full sized footing. Therefore the following facts should be considered in interpretation of the load test results.

Bearing Capacity And settlement (Terzaghi)

a) Bearing Capacity of Cohesive Soil.

$q_{(footing)} = q_{(plate)}$, (1)

where q is the ultimate bearing capacity.

b) Bearing Capacity of Cohesionless Soil.

$q_{(footing)} = q_{(plate)} * (B/b)$ (2)

where B = footing width, b = plate wide (0.457m)

c) Settlement of Cohesive Soil.

$S_{(footing)} = S_{(plate)} * (B/b)$ (3)

where S is the settlement.

d) Settlement of Cohesionless Soil.

$S_{(footing)} = S_{(plate)} * [\{B*(b+0.3)\}/\{b*(B+0.3)\}]2$ (4)

B & b in meters.

Load Bearing Capacity using two Plates (Housel)

$Q_1 = A_1 m + P_1 n$ For plate **1** (5)

$Q_2 = A_2 m + P_2 n$ For plate **2** (6)

$Q_f = A_f m + P_f n$ For footing (7)

Allowable Bearing Capacity:

From the results of the plate load test the Ultimate bearing Capacity (q_{ult}) and corresponding settlement against shear failure are listed on the following table:

for plate = 0.457 m.

q_{ult} t/m^2	**S(failure) mm**
70	25

for plate = 0.30 m.

q_{ult} t/m^2	**S (failure) mm**
68	20.5

Using Eq (2), the ultimate bearing capacity of the footing are listed in the following table for B=16m :

for plate = 0.457 m.

q_{ult} (Plate) t/m^2	q_{ult} (Mat) t/m^2	q_{all} (Mat) t/m^2
70	2450.76	490.15

for plate = 0.30 m.

q_{ult} (Plate) t/m^2	q_{ult} (Mat) t/m^2	q_{all} (Mat) t/m^2
68	3626.67	725.33

For allowable bearing capacity calculation, a high factor of safety(5) should be used.

Bearing Capacity /Settlement Failure :

For Plate 45.7 cm

For settlement control of 25 mm, 40 mm and 50 mm and by using Eqn (4) and relevant curves the following results can be obtained : 1

Footing Width B (m)	**16**	**16**	**16**
Plate width b (m)	0.457	0.457	0.457
Sett. footing (mm)	25	40	50
Sett. plate(mm)	9.45	15.13	18.91
q_{all} (t/m^2)	47	58	63

For Plate 30 cm

For settlement control of 25 mm, 40 mm and 50 mm and by using Eqn (4) and relevant curves the following results can be obtained :

Footing Width B (m)	**16**	**16**	**16**
Plate width b (m)	0.30	0.30	0.30
Sett. footing (mm)	25	40	50
Sett. Plate (mm)	6.49	10.38	12.97
q_{all} (t/m^2)	37	49	55

Allowable Bearing Capacity Using Equations 5, 6 and 7 (Housel)

A1=0.0707 , P1 = 0.942 For plate 0.30m, and Q1 = 4.8 ton (For S = 20.64mm)

A2=0.164 , P2 = 1.435 For plate 0.457m, and Q2 = 10.66 ton (For S = 20.64mm)

Solving Eqn's 5 & 6 : m = 59.39, and n = 0.6367, Therefore :

Footing Width B (m)	16
Q (ton)	15245
q_{ult} (t/m^2)	59.55
q_{all} (t/m^2)	14.9

A factor of Safety of 4 is used

Plate load Tests

Group 2

Test No. 1

Loading Stages	Time (min)	Load (ton)	Stress ton/m2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVG SETT.
				G_1	G_2	G_3	S_1	S_2	S_3	(mm)
Initial Reading Loading	0.00	0	0	27.76	46.20	6.00	0.00	0.00	0.00	***0.00***
	5.00	2	12.19	26.34	45.54	5.20	1.42	0.66	0.80	**0.96**
	10.00			26.31	45.45	5.15	1.45	0.75	0.85	**1.02**
	15.00			26.27	45.38	5.08	1.49	0.82	0.92	**1.08**
	5.00	4	24.39	25.87	44.28	4.20	1.89	1.92	1.80	**1.87**
	10.00			25.84	44.20	4.15	1.92	2.00	1.85	**1.92**
	15.00			25.83	44.12	4.10	1.93	2.08	1.90	**1.97**
	5.00	6	36.58	25.32	43.90	3.15	2.44	2.30	2.85	**2.53**
	10.00			25.28	43.85	3.12	2.48	2.35	2.88	**2.57**
	15.00			25.26	43.81	3.08	2.50	2.39	2.92	**2.60**
	5.00	8	48.77	24.45	41.13	2.76	3.31	5.07	3.24	**3.87**
	10.00			24.41	41.03	2.68	3.35	5.17	3.32	**3.95**
	15.00			24.40	40.95	2.65	3.36	5.25	3.35	**3.99**
	5.00	10	60.96	22.90	39.46	0.96	4.86	6.74	5.04	**5.55**
	10.00			22.85	39.39	0.93	4.91	6.81	5.07	**5.60**
	15.00			22.81	39.37	0.90	4.95	6.83	5.10	**5.63**
	5.00	12	73.16	21.15	36.27	48.12	6.61	9.93	7.88	**8.14**
	10.00			20.96	36.15	48.09	6.80	10.05	7.91	**8.25**
	15.00			20.93	36.12	48.08	6.83	10.08	7.92	**8.28**
	5.00	12	73.16	21.15	36.27	48.12	6.61	9.93	7.88	**8.14**
	10.00			20.96	36.15	48.09	6.80	10.05	7.91	**8.25**
	15.00			20.93	36.12	48.08	6.83	10.08	7.92	**8.28**

Test No. 2

Loading Stages	Time (min)	Load (ton)	Stress ton/m2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVG SETT.
				G_1	G_2	G_3	S_1	S_2	S_3	(mm)
Initial Reading Loading	0.00	0	0	49.05	31.08	13.94	0.00	0.00	0.00	***0.00***
	5.00	2	12.19	48.40	30.32	13.20	0.65	0.76	0.74	**0.72**
	10.00			48.38	30.17	13.15	0.67	0.91	0.79	**0.79**
	15.00			48.35	30.10	13.10	0.70	0.98	0.84	**0.84**
	5.00	4	24.39	47.93	28.95	12.20	1.12	2.13	1.74	**1.66**
	10.00			47.90	28.90	12.18	1.15	2.18	1.76	**1.70**
	15.00			47.88	28.84	12.12	1.17	2.24	1.82	**1.74**
	5.00	6	36.58	46.16	26.61	10.68	2.89	4.47	3.26	**3.54**
	10.00			46.13	26.54	10.64	2.92	4.54	3.30	**3.59**
	15.00			46.06	26.41	10.60	2.99	4.67	3.34	**3.67**
	5.00	8	48.77	45.46	21.32	7.13	3.59	9.76	6.81	**6.72**
	10.00			45.35	21.16	7.10	3.70	9.92	6.84	**6.82**
	15.00			45.33	20.90	7.00	3.72	10.18	6.94	**6.95**
	5.00	10	60.96	41.81	16.50	5.30	7.24	14.58	8.64	**10.15**
	10.00			41.65	16.45	5.26	7.40	14.63	8.68	**10.24**
	15.00			41.50	16.16	5.20	7.55	14.92	8.74	**10.40**
	5.00	11.2	68.28	35.81	10.50	0.10	13.24	20.58	13.84	**15.89**
	10.00			35.65	10.45	0.06	13.40	20.63	13.88	**15.97**
	15.00			35.50	10.16	0.00	13.55	20.92	13.94	**16.14**

Test No. 3

Loading Stages	Time (min)	Load (ton)	Stress ton/m2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVG SETT.
				G_1	G_2	G_3	S_1	S_2	S_3	(mm)
Initial Reading Loading	0.00	0	0	12.66	49.97	31.02	0.00	0.00	0.00	***0.00***
	5.00	2	12.19	11.43	49.04	29.59	1.23	0.93	1.43	**1.20**
	10.00			11.41	48.95	29.58	1.25	1.02	1.44	**1.24**
	15.00			11.39	48.92	29.57	1.27	1.05	1.45	**1.26**
	5.00	4	24.39	11.01	47.75	29.06	1.65	2.22	1.96	**1.94**
	10.00			10.99	47.65	29.05	1.67	2.32	1.97	**1.99**
	15.00			10.98	47.55	29.05	1.68	2.42	1.97	**2.02**
	5.00	6	36.58	10.28	46.05	28.33	2.38	3.92	2.69	**3.00**
	10.00			10.22	45.88	28.32	2.44	4.09	2.70	**3.08**
	15.00			10.16	45.80	28.31	2.50	4.17	2.71	**3.13**
	5.00	8	48.77	9.10	43.30	27.60	3.56	6.67	3.42	**4.55**
	10.00			8.93	43.20	27.58	3.73	6.77	3.44	**4.65**
	15.00			8.85	43.05	27.27	3.81	6.92	3.75	**4.83**
	5.00	10	60.96	6.95	37.80	25.41	5.71	12.17	5.61	**7.83**
	10.00			6.80	37.65	25.40	5.86	12.32	5.62	**7.93**
	15.00			6.70	37.55	25.39	5.96	12.42	5.63	**8.00**
	5.00	10.8	65.84	4.95	35.80	23.41	7.71	14.17	7.61	**9.83**
	10.00			4.80	35.65	23.40	7.86	14.32	7.62	**9.93**
	15.00			4.70	35.55	23.39	7.96	14.42	7.63	**10.00**

Test No. 4

Loading Stages	Time (min)	Load (ton)	Stress ton/m2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVG SETT.
				G_1	G_2	G_3	S_1	S_2	S_3	(mm)
Initial Reading Loading	0.00	0	0	12.00	23.23	44.67	0.00	0.00	0.00	***0.00***
	5.00	2	12.19	11.31	21.60	43.95	0.69	1.63	0.72	**1.01**
	10.00			11.25	21.50	43.92	0.75	1.73	0.75	**1.08**
	15.00			11.20	21.30	43.80	0.80	1.93	0.87	**1.20**
	5.00	4	24.39	11.10	20.00	42.81	0.90	3.23	1.86	**2.00**
	10.00			10.90	19.55	42.75	1.10	3.68	1.92	**2.23**
	15.00			10.70	19.40	42.68	1.30	3.83	1.99	**2.37**
	5.00	6	36.58	9.70	15.10	40.75	2.30	8.13	3.92	**4.78**
	10.00			9.50	14.67	40.54	2.50	8.56	4.13	**5.06**
	15.00			9.25	14.23	40.38	2.75	9.00	4.29	**5.35**
	5.00	8	48.77	7.89	10.59	38.65	4.11	12.64	6.02	**7.59**
	10.00			7.44	10.12	37.99	4.56	13.11	6.68	**8.12**
	15.00			7.15	10.03	37.94	4.85	13.20	6.73	**8.26**
	5.00	8.8	53.65	6.38	8.27	36.85	5.62	14.96	7.82	**9.47**
	10.00			6.02	7.72	36.73	5.98	15.51	7.94	**9.81**
	15.00			5.82	7.32	36.65	6.18	15.91	8.02	**10.04**

Test No. 5

Loading Stages	Time (min)	Load (ton)	Stress ton/m2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVG SETT.
				G_1	G_2	G_3	S_1	S_2	S_3	(mm)
Initial Reading Loading	0.00	0	0	27.96	44.85	3.09	0.00	0.00	0.00	***0.00***
	5.00	2	12.19	26.91	43.26	1.76	1.05	1.59	1.33	**1.32**
	10.00			26.85	43.23	1.66	1.11	1.62	1.43	**1.39**
	15.00			26.82	43.21	1.58	1.14	1.64	1.51	**1.43**
	5.00	4	24.39	26.33	42.89	0.98	1.63	1.96	2.11	**1.90**
	10.00			26.23	42.82	0.85	1.73	2.03	2.24	**2.00**
	15.00			26.22	42.81	0.79	1.74	2.04	2.30	**2.03**
	5.00	6	36.58	25.45	41.29	49.97	2.51	3.56	3.12	**3.06**
	10.00			25.41	41.25	49.96	2.55	3.60	3.13	**3.09**
	15.00			25.35	41.20	49.95	2.61	3.65	3.14	**3.13**
	5.00	8	48.77	24.52	40.54	48.10	3.44	4.31	4.99	**4.25**
	10.00			24.47	40.50	48.07	3.49	4.35	5.02	**4.29**
	15.00			24.41	40.45	48.03	3.55	4.40	5.06	**4.34**
	5.00	10	60.96	23.33	39.31	47.09	4.63	5.54	6.00	**5.39**
	10.00			23.22	39.25	46.96	4.74	5.60	6.13	**5.49**
	15.00			23.17	39.21	46.95	4.79	5.64	6.14	**5.52**
	5.00	12	73.16	21.77	38.40	44.66	6.19	6.45	8.43	**7.02**
	10.00			21.73	38.39	44.64	6.23	6.46	8.45	**7.05**
	15.00			21.69	38.38	44.62	6.27	6.47	8.47	**7.07**
	5.00	12.4	75.60	20.77	37.40	43.66	7.19	7.45	9.43	**8.02**
	10.00			20.73	37.39	43.64	7.23	7.46	9.45	**8.05**
	15.00			20.69	37.38	43.62	7.27	7.47	9.47	**8.07**

Test No. 6

Loading Stages	Time (min)	Load (ton)	Stress ton/m2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVG SETT.
				G_1	G_2	G_3	S_1	S_2	S_3	(mm)
Initial Reading Loading	0.00	0	0	28.52	47.66	0.58	0.00	0.00	0.00	***0.00***
	5.00	2	12.19	27.75	46.60	49.65	0.77	1.06	0.93	**0.92**
	10.00			27.73	46.56	49.62	0.79	1.10	0.96	**0.95**
	15.00			27.70	46.55	49.61	0.82	1.11	0.97	**0.97**
	5.00	4	24.39	26.21	45.49	49.05	2.31	2.17	1.53	**2.00**
	10.00			26.18	45.48	49.02	2.34	2.18	1.56	**2.03**
	15.00			26.15	45.47	49.00	2.37	2.19	1.58	**2.05**
	5.00	6	36.58	25.40	45.35	48.41	3.12	2.31	2.17	**2.53**
	10.00			25.37	45.34	48.37	3.15	2.32	2.21	**2.56**
	15.00			25.34	45.33	48.35	3.18	2.33	2.23	**2.58**
	5.00	8	48.77	24.35	45.19	47.72	4.17	2.47	2.86	**3.17**
	10.00			24.32	45.18	47.69	4.20	2.48	2.89	**3.19**
	15.00			24.31	45.17	47.65	4.21	2.49	2.93	**3.21**
	5.00	10	60.96	23.15	44.33	46.85	5.37	3.33	3.73	**4.14**
	10.00			23.04	44.25	46.84	5.48	3.41	3.74	**4.21**
	15.00			23.02	44.20	46.82	5.50	3.46	3.76	**4.24**
	5.00	12	73.16	22.50	43.00	45.36	6.02	4.66	5.22	**5.30**
	10.00			22.45	42.95	45.35	6.07	4.71	5.23	**5.34**
	15.00			22.41	42.87	45.33	6.11	4.79	5.25	**5.38**
	5.00	12.4	75.60	21.50	42.00	44.36	7.02	5.66	6.22	**6.30**
	10.00			21.45	41.95	44.35	7.07	5.71	6.23	**6.34**
	15.00			21.41	41.87	44.33	7.11	5.79	6.25	**6.38**

Group 3

Test No. 1

Loading Stages	Time (min)	Load (ton)	Stress ton/m2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVG SETT.
				G_1	G_2	G_3	S_1	S_2	S_3	(mm)
Initial Reading Loading	0.00	0	0	20.35	44.36	47.24	0.00	0.00	0.00	***0.00***
	5.00	2	12.19	19.50	42.32	46.88	0.85	2.04	0.36	**1.08**
	10.00			19.45	42.20	46.87	0.90	2.16	0.37	**1.14**
	15.00			19.40	42.12	46.86	0.95	2.24	0.38	**1.19**
	5.00	4	24.39	18.75	41.35	46.53	1.60	3.01	0.71	**1.77**
	10.00			18.65	41.26	46.50	1.70	3.10	0.74	**1.85**
	15.00			18.60	41.17	46.45	1.75	3.19	0.79	**1.91**
	5.00	6	36.58	17.74	40.20	45.84	2.61	4.16	1.40	**2.72**
	10.00			17.67	40.15	45.81	2.68	4.21	1.43	**2.77**
	15.00			17.61	40.05	45.79	2.74	4.31	1.45	**2.83**
	5.00	8	48.77	16.56	39.81	44.90	3.79	4.55	2.34	**3.56**
	10.00			16.49	39.71	44.85	3.86	4.65	2.39	**3.63**
	15.00			16.40	39.60	44.77	3.95	4.76	2.47	**3.73**
	5.00	10	60.96	14.56	37.71	42.12	5.79	6.65	5.12	**5.85**
	10.00			14.45	37.61	42.03	5.90	6.75	5.21	**5.95**
	15.00			14.36	37.50	41.91	5.99	6.86	5.33	**6.06**
	5.00	12	73.16	9.65	32.45	37.35	10.70	11.91	9.89	**10.83**
	10.00			9.40	32.23	37.20	10.95	12.13	10.04	**11.04**
	15.00			9.10	32.20	37.03	11.25	12.16	10.21	**11.21**

Test No. 2

Loading Stages	Time (min)	Load (ton)	Stress ton/m2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVG SETT.
				G_1	G_2	G_3	S_1	S_2	S_3	(mm)
Initial Reading Loading	0.00	0	0	4.50	24.73	48.90	0.00	0.00	0.00	***0.00***
	5.00	2	12.19	4.24	23.32	48.13	0.26	1.41	0.77	**0.81**
	10.00			4.20	23.31	48.05	0.30	1.42	0.85	**0.86**
	15.00			4.18	23.30	48.04	0.32	1.43	0.86	**0.87**
	5.00	4	24.39	2.95	21.62	47.48	1.55	3.11	1.42	**2.03**
	10.00			2.92	21.59	47.44	1.58	3.14	1.46	**2.06**
	15.00			2.88	21.54	47.42	1.62	3.19	1.48	**2.10**
	5.00	6	36.58	0.44	19.70	46.60	4.06	5.03	2.30	**3.80**
	10.00			0.42	19.62	46.54	4.08	5.11	2.36	**3.85**
	15.00			0.36	19.54	46.50	4.14	5.19	2.40	**3.91**
	5.00	8	48.77	49.44	17.41	45.30	5.06	7.32	3.60	**5.33**
	10.00			49.40	17.25	45.24	5.10	7.48	3.66	**5.41**
	15.00			49.35	17.20	45.20	5.15	7.53	3.70	**5.46**
	5.00	10	60.96	45.56	14.97	43.53	8.94	9.76	5.37	**8.02**
	10.00			45.52	14.92	43.52	8.98	9.81	5.38	**8.06**
	15.00			45.47	14.90	43.51	9.03	9.83	5.39	**8.08**
	5.00	12	73.16	33.50	48.71	37.58	21.00	26.02	11.32	**19.45**
	10.00			33.47	48.69	37.58	21.03	26.04	11.32	**19.46**
	15.00			33.46	48.67	37.57	21.04	26.06	11.33	**19.48**

Test No. 3

Loading Stages	Time (min)	Load (ton)	Stress ton/m2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVG SETT.
				G_1	G_2	G_3	S_1	S_2	S_3	(mm)
Initial Reading Loading	0.00	0	0	25.00	2.95	49.37	0.00	0.00	0.00	***0.00***
	5.00	2	12.19	24.00	0.72	48.74	1.00	2.23	0.63	**1.29**
	10.00			23.93	0.64	48.73	1.07	2.31	0.64	**1.34**
	15.00			23.85	0.55	48.72	1.15	2.40	0.65	**1.40**
	5.00	4	24.39	22.97	49.75	47.10	2.03	3.20	2.27	**2.50**
	10.00			22.91	49.67	47.09	2.09	3.28	2.28	**2.55**
	15.00			22.84	49.61	47.07	2.16	3.34	2.30	**2.60**
	5.00	6	36.58	21.74	48.70	46.42	3.26	4.25	2.95	**3.49**
	10.00			21.65	48.63	46.40	3.35	4.32	2.97	**3.55**
	15.00			21.60	48.57	46.37	3.40	4.38	3.00	**3.59**
	5.00	8	48.77	19.70	47.01	45.30	5.30	5.94	4.07	**5.10**
	10.00			19.51	46.90	45.25	5.49	6.05	4.12	**5.22**
	15.00			19.42	46.82	45.23	5.58	6.13	4.14	**5.28**
	5.00	10	60.96	17.32	44.45	44.66	7.68	8.50	4.71	**6.96**
	10.00			16.80	44.11	44.56	8.20	8.84	4.81	**7.28**
	15.00			16.60	43.90	44.52	8.40	9.05	4.85	**7.43**
	5.00	12	73.16	9.40	39.90	41.25	15.60	13.05	8.12	**12.26**
	10.00			9.20	39.75	41.24	15.80	13.20	8.13	**12.38**
	15.00			9.09	39.67	41.23	15.91	13.28	8.14	**12.44**
	5.00	12.4	75.60	8.40	38.90	40.25	16.60	14.05	9.12	**13.26**
	10.00			8.20	38.75	40.24	16.80	14.20	9.13	**13.38**
	15.00			8.09	38.67	40.23	16.91	14.28	9.14	**13.44**

Test No. 4

Loading Stages	Time (min)	Load (ton)	Stress ton/m2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVG SETT.
				G_1	G_2	G_3	S_1	S_2	S_3	(mm)
Initial Reading Loading	0.00	0	0	27.41	3.22	49.90	0.00	0.00	0.00	***0.00***
	5.00	2	12.19	26.00	2.26	48.06	1.41	0.96	1.84	**1.40**
	10.00			25.91	2.20	48.05	1.50	1.02	1.85	**1.46**
	15.00			25.85	2.18	48.03	1.56	1.04	1.87	**1.49**
	5.00	4	24.39	24.73	1.44	47.30	2.68	1.78	2.60	**2.35**
	10.00			24.71	1.37	47.29	2.70	1.85	2.61	**2.39**
	15.00			24.65	1.27	47.19	2.76	1.95	2.71	**2.47**
	5.00	6	36.58	23.43	0.43	46.48	3.98	2.79	3.42	**3.40**
	10.00			23.35	0.36	46.44	4.06	2.86	3.46	**3.46**
	15.00			23.23	0.31	46.39	4.18	2.91	3.51	**3.53**
	5.00	8	48.77	21.32	48.71	45.37	6.09	4.51	4.53	**5.04**
	10.00			21.16	48.60	45.32	6.25	4.62	4.58	**5.15**
	15.00			21.10	48.50	45.26	6.31	4.72	4.64	**5.22**
	5.00	10	60.96	17.90	44.36	43.88	9.51	8.86	6.02	**8.13**
	10.00			17.83	44.19	43.85	9.58	9.03	6.05	**8.22**
	15.00			17.75	44.15	43.78	9.66	9.07	6.12	**8.28**
	5.00	12	73.16	13.58	41.85	40.32	13.83	11.37	9.58	**11.59**
	10.00			13.52	41.80	40.32	13.89	11.42	9.58	**11.63**
	15.00			13.33	41.70	40.31	14.08	11.52	9.59	**11.73**
	5.00	12.4	75.60	12.58	40.85	39.32	14.83	12.37	10.58	**12.59**
	10.00			12.52	40.80	39.32	14.89	12.42	10.58	**12.63**
	15.00			12.33	40.7	39.31	15.08	12.52	10.59	**12.73**

Test No. 5

Loading Stages	Time (min)	Load (ton)	Stress ton/m2	GAUGE READING (0.01mm)			SETTLEMENT (mm)			AVG SETT.
				G_1	G_2	G_3	S_1	S_2	S_3	(mm)
Initial Reading Loading	0.00	0	0	44.80	3.37	24.72	0.00	0.00	0.00	***0.00***
	5.00	2	12.19	44.29	2.02	24.17	0.51	1.35	0.55	**0.80**
	10.00			44.20	1.93	24.15	0.60	1.44	0.57	**0.87**
	15.00			44.14	1.83	24.12	0.66	1.54	0.60	**0.93**
	5.00	4	24.39	43.44	0.61	23.66	1.36	2.76	1.06	**1.73**
	10.00			43.36	0.43	23.53	1.44	2.94	1.19	**1.86**
	15.00			43.33	0.35	23.51	1.47	3.02	1.21	**1.90**
	5.00	6	36.58	42.40	48.95	22.90	2.40	4.42	1.82	**2.88**
	10.00			42.30	48.80	22.88	2.50	4.57	1.84	**2.97**
	15.00			42.25	48.67	22.84	2.55	4.70	1.88	**3.04**
	5.00	8	48.77	40.61	46.36	21.99	4.19	7.01	2.73	**4.64**
	10.00			40.53	46.26	21.96	4.27	7.11	2.76	**4.71**
	15.00			22.02	5.30	9.55	22.78	48.07	15.17	**28.67**
	5.00	10	60.96	40.46	46.14	21.93	4.34	7.23	2.79	**4.79**
	10.00			37.75	42.18	20.40	7.05	11.19	4.32	**7.52**
	15.00			37.65	41.90	20.33	7.15	11.47	4.39	**7.67**
	5.00	12	73.16	37.50	41.83	20.32	7.30	11.54	4.40	**7.75**
	10.00			29.48	30.45	17.15	15.32	22.92	7.57	**15.27**
	15.00			29.29	30.34	17.14	15.51	23.03	7.58	**15.37**
	5.00	12.4	75.60	29.20	29.00	17.13	15.60	24.37	7.59	**15.85**
	10.00			28.48	29.45	16.15	16.32	23.92	8.57	**16.27**
	15.00			28.29	29.34	16.14	16.51	24.03	8.58	**16.37**

Figure C.1: A photo shows plate load set up and instrumentations

Figure C.2: A photo depicts the shape of failure seen on site in the sandy soil

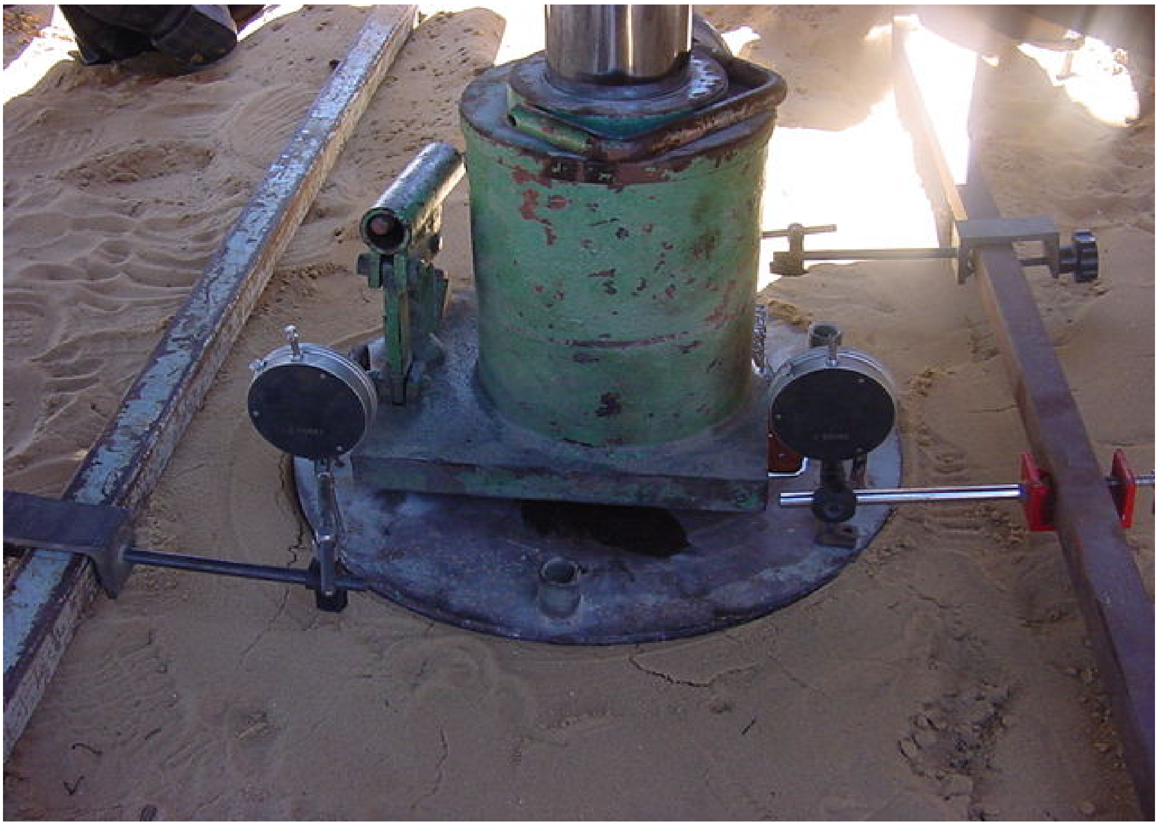

Figure C.3: A photo shows the load cell, strain gauges and the reference beams

Figure C.4: A close up picture of the failure occurred in the sandy soil on site

Figure C.5: A photo shows a radial failure occurred while performing load plate test on the sandy soil on site around plate of 45 cm diameter

Figure C.6: A photo shows the adjustment plate load and strain gauges in field